The impact of galactic fountains on the global evolution of galaxy disks

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The impact of galactic fountain on disc evolution

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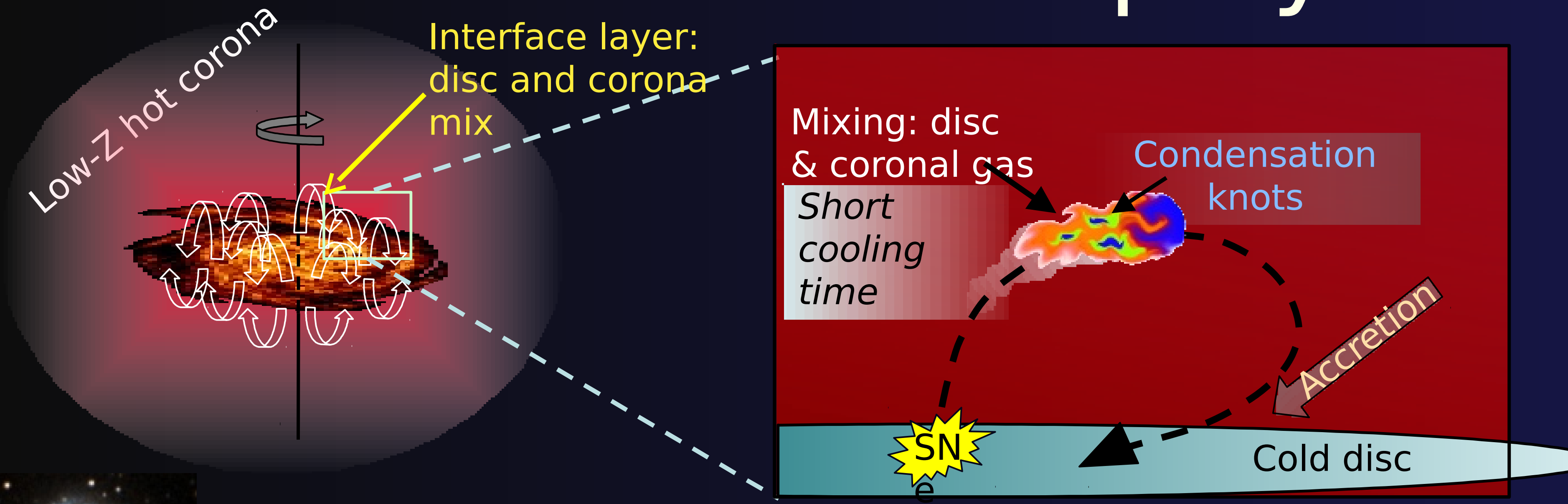
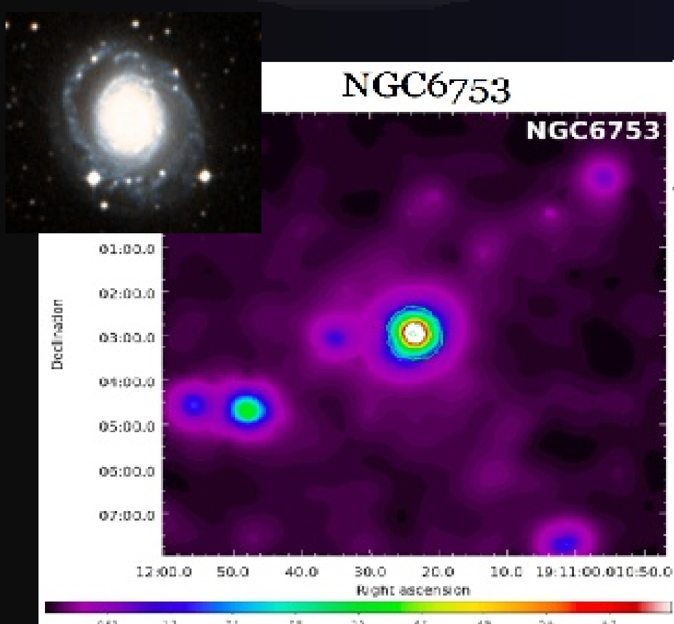
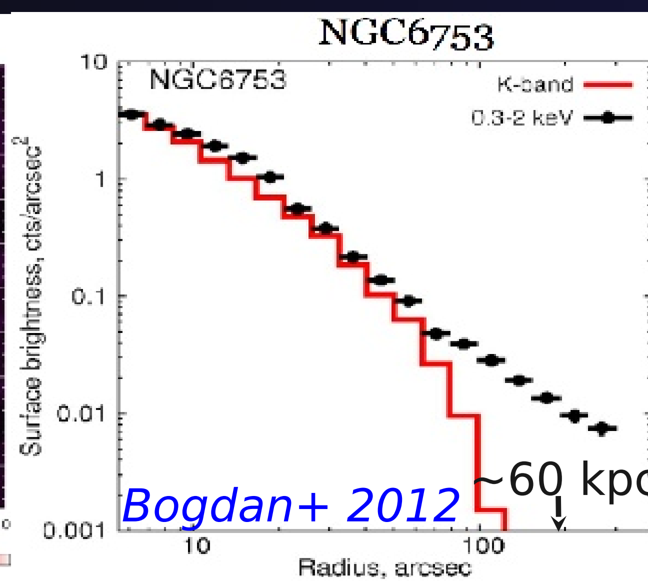
Disc-corona interplay







Anderson & Bregman 2012
Dai+ 2012, Anderson+ 2013

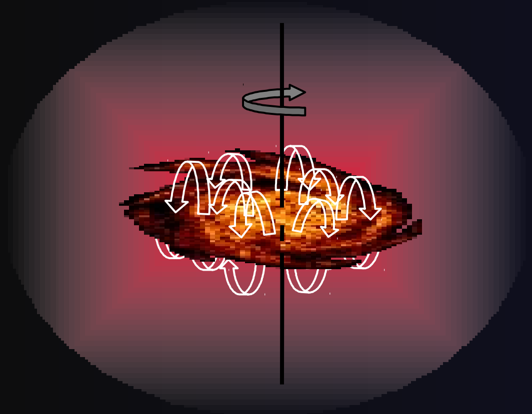
MW *Miller & Bregman+ 2013, 2015; Gatto+13*

Mass corona ~ 10-50% missing baryons

Cooling rate ~ 0.1 Mo/yr

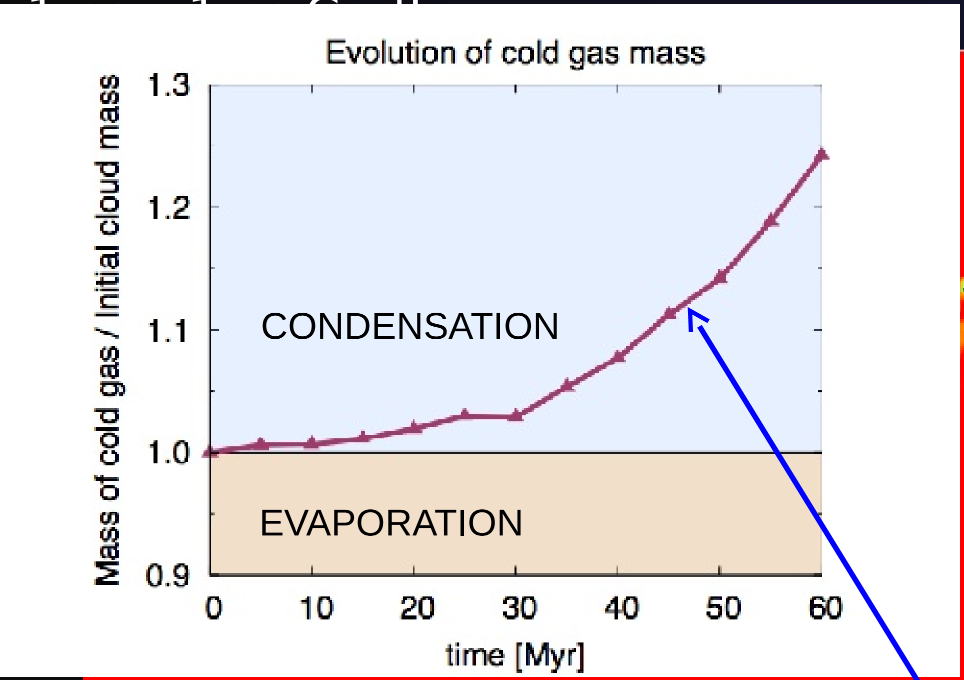
Global process:
Fountain-driven gas accretion

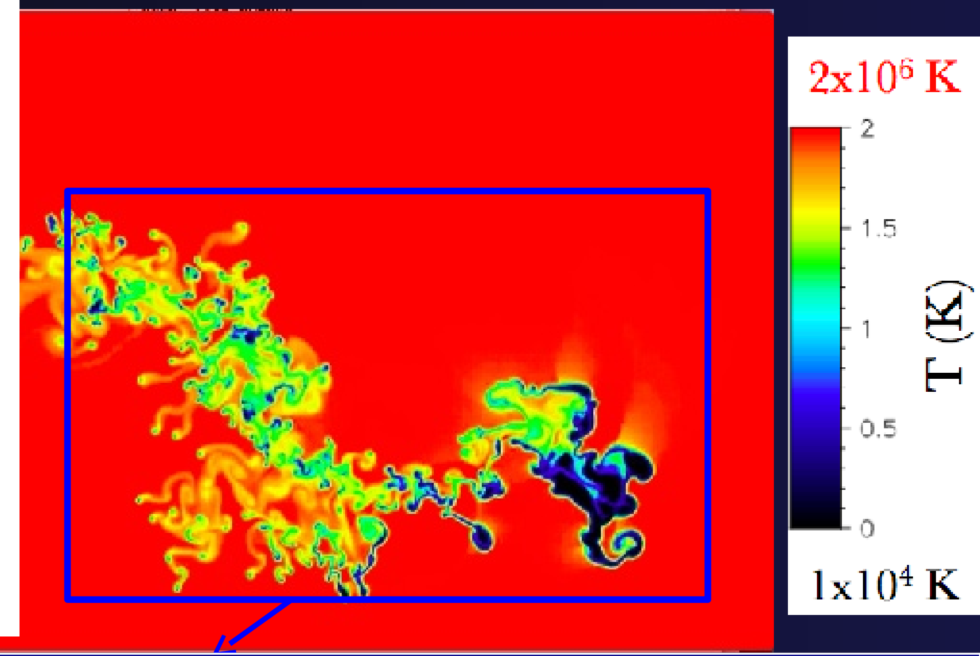
Disc-cloud corona interaction



Tcorona=2x106 K Zcorona=0.1 Z

Zcloud=1 Z



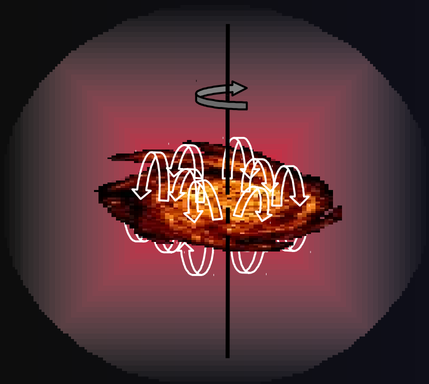


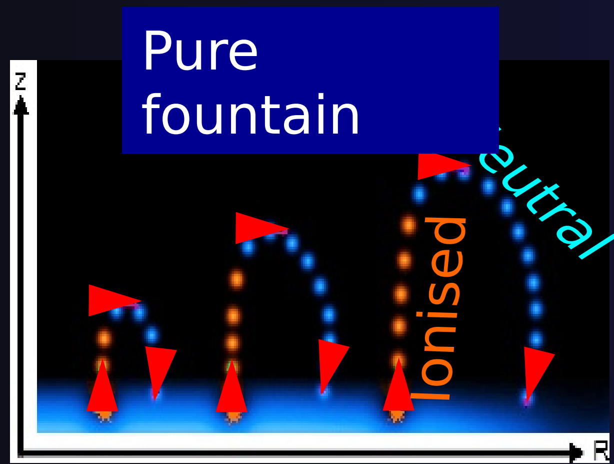
Mass of cold gas increased by ~20%!

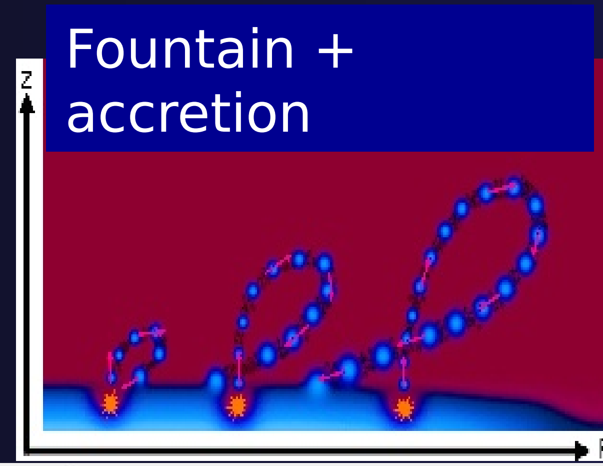
Marinacci, et al. 2010, 2011, MNRAS

Lucia Armillotta

Global fountain

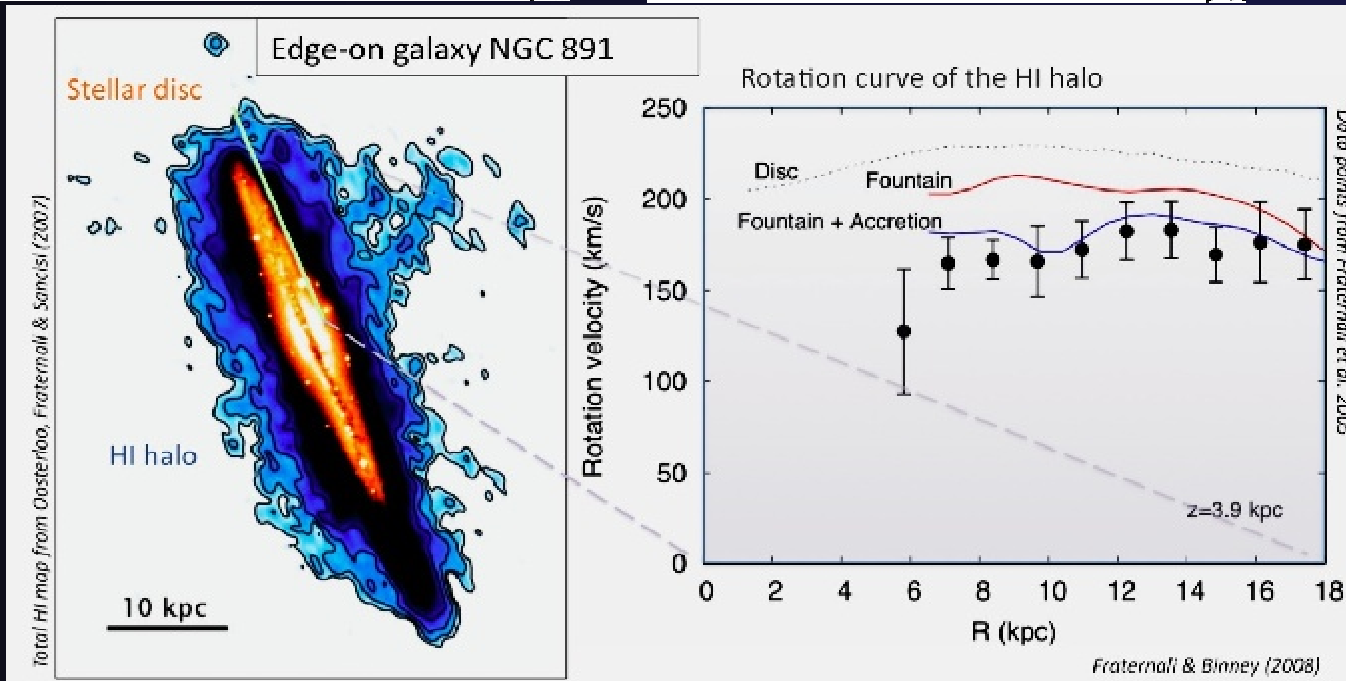






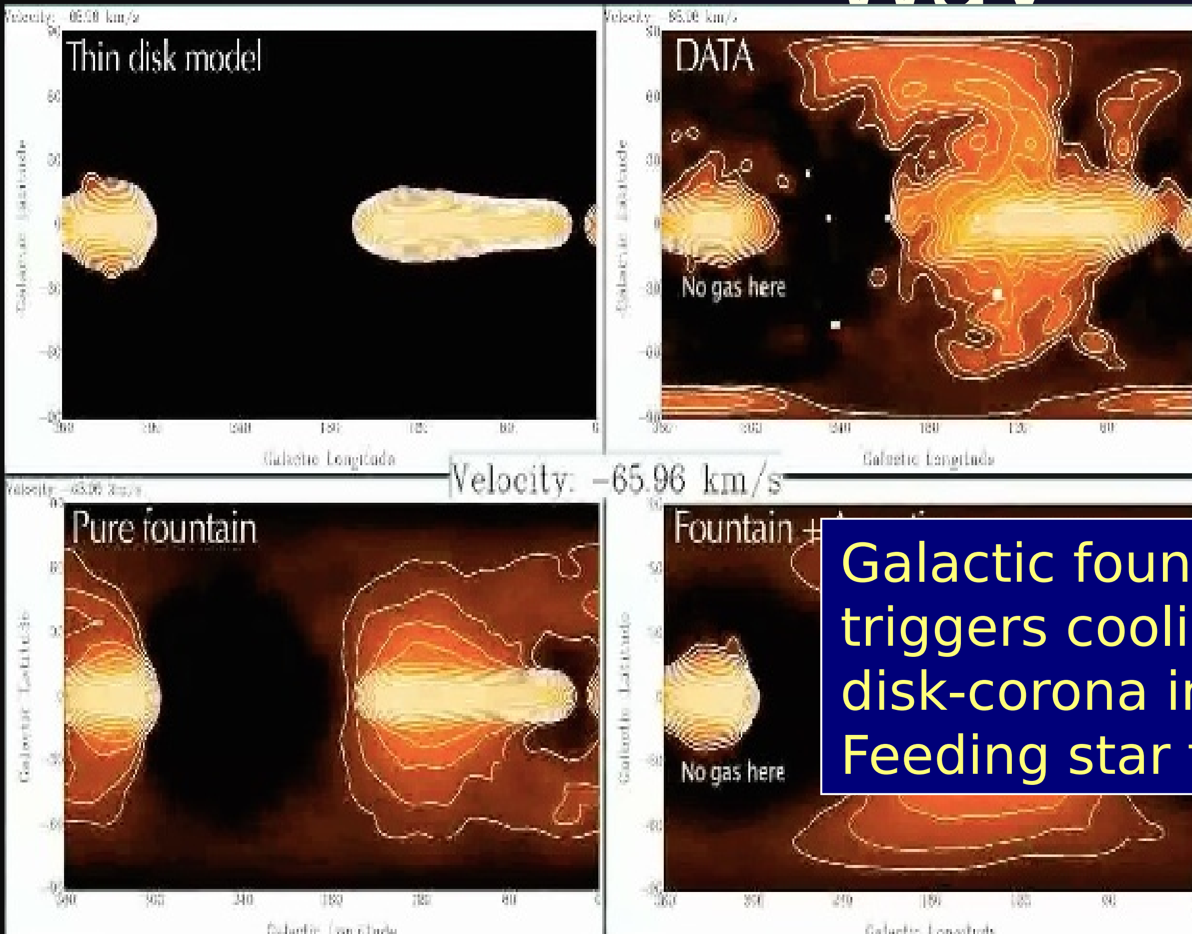
Best-fit Accretion Rate ~ 3 M yr-1

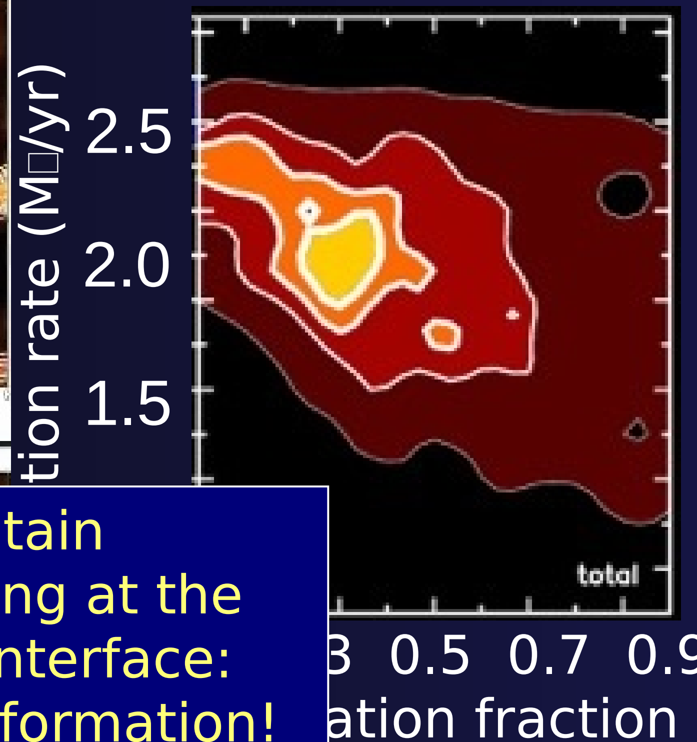
Compare to SFR ~ 4 M yr-1



Fraternali & Binney 2008, MNRAS; Marinacci, Fraternali+ 2011, MNRAS

Extraplanar HI in the Milky Way





Galactic fountain triggers cooling at the disk-corona interface: Feeding star formation!

Marasco, Fraternali & Binney 2012, MNRAS

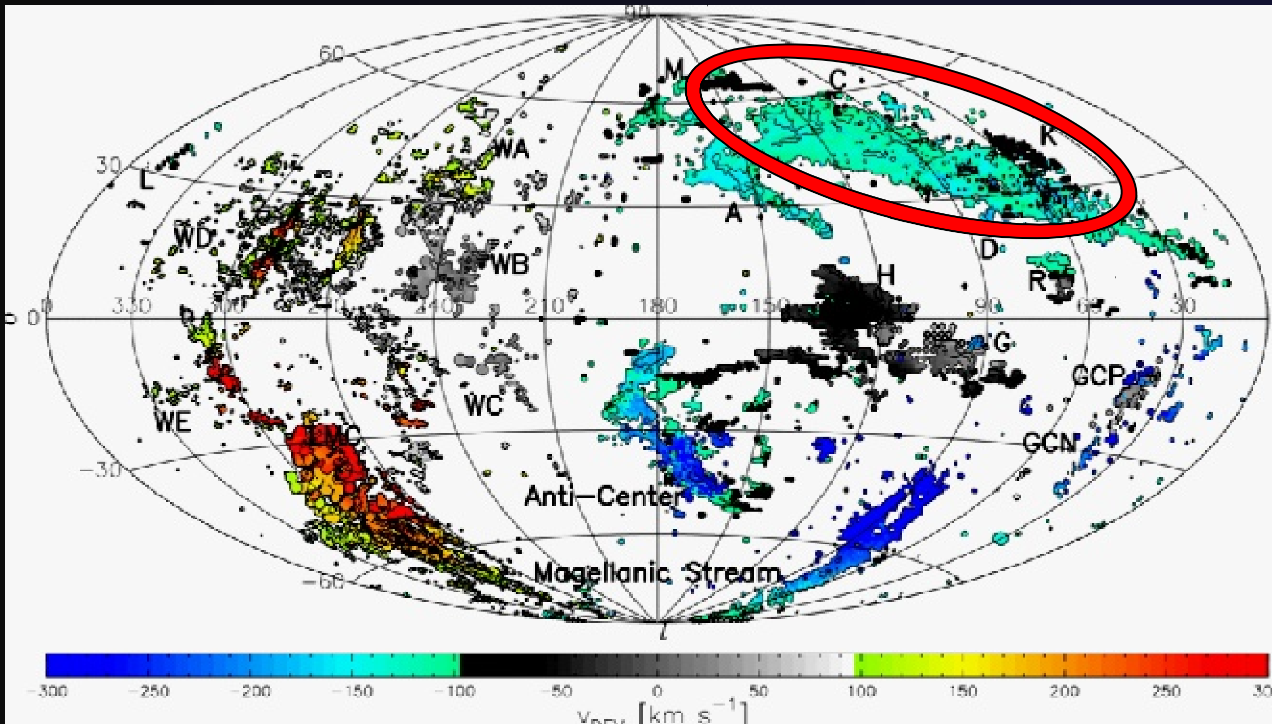
Best-fit Accretion Rate ~ 2 Myr-1

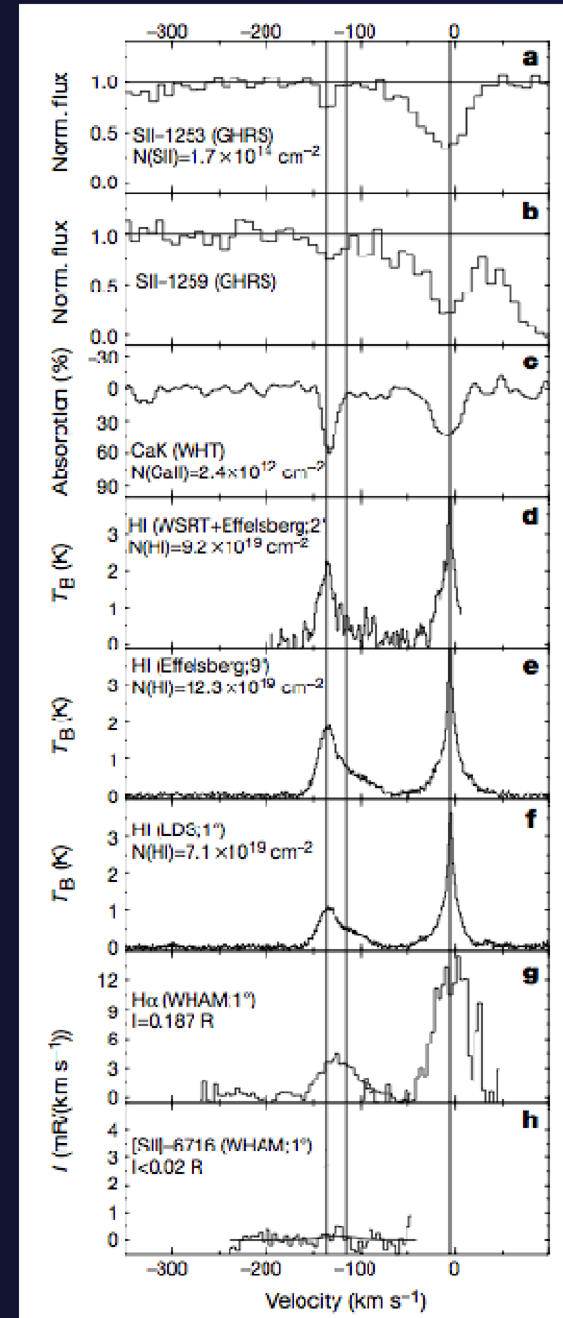
Compare to SFR ~ 1-3 Myr-1

Local process:

Galactic hail: origin of the High Velocity Cloud complex C

Origin of HVCs





Oort 70 leftover of galaxy formation

Bregman 80 Galactic fountain

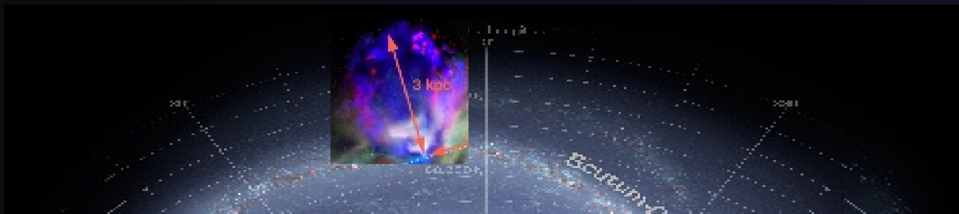
+ satellites (*Olano 2001*), thermal instabilities (*Kaufmann+ 06*), no thermal instabilities (*Binney+ 09*), filaments (*Fernandez+ 12*)

Wakker+ 1999, Nat Z~0.1 Solar -> Accretion!

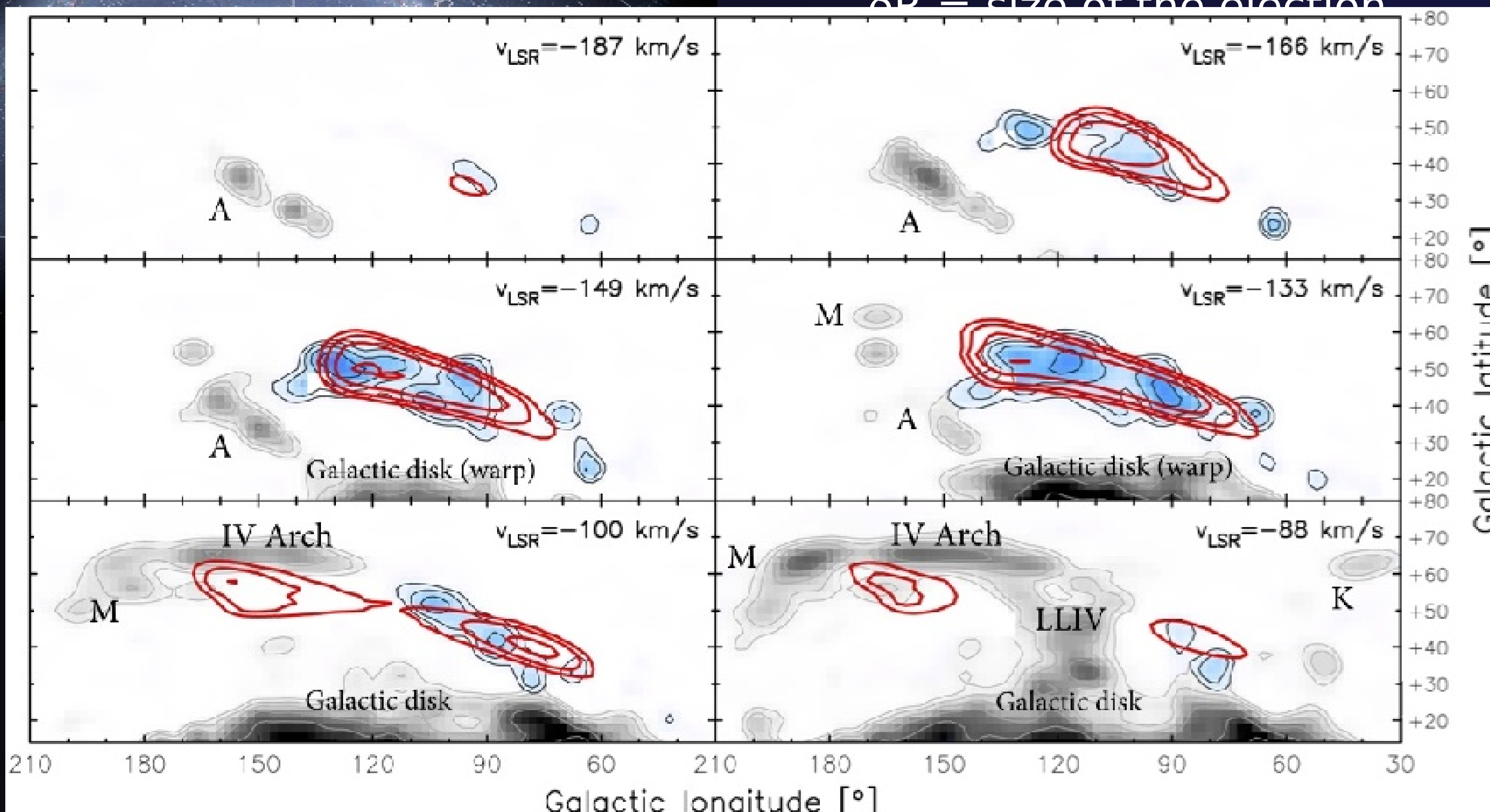
Gibson+ 2001 Z~0.3 Accretion?

Collins+ 2007 overabundance α elements (SN II?)

Formation of complex C

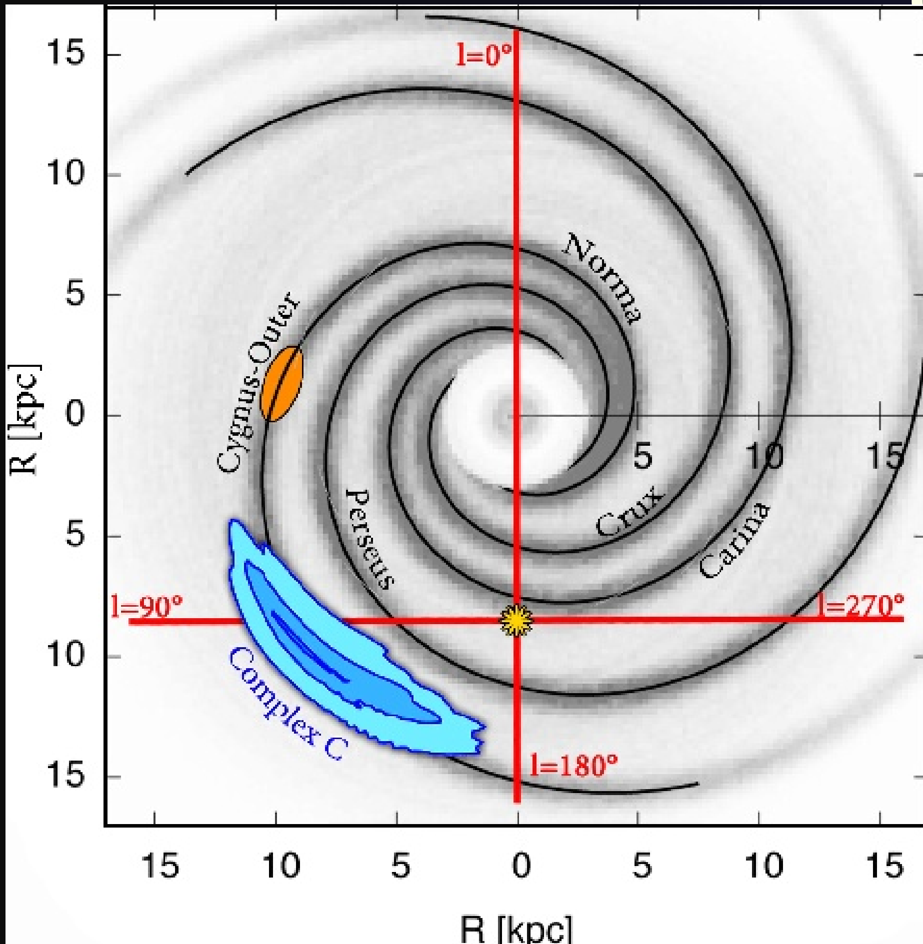


Six free parameters:
V0 = ejection velocity
R0 = ejection location
δR = size of the ejection

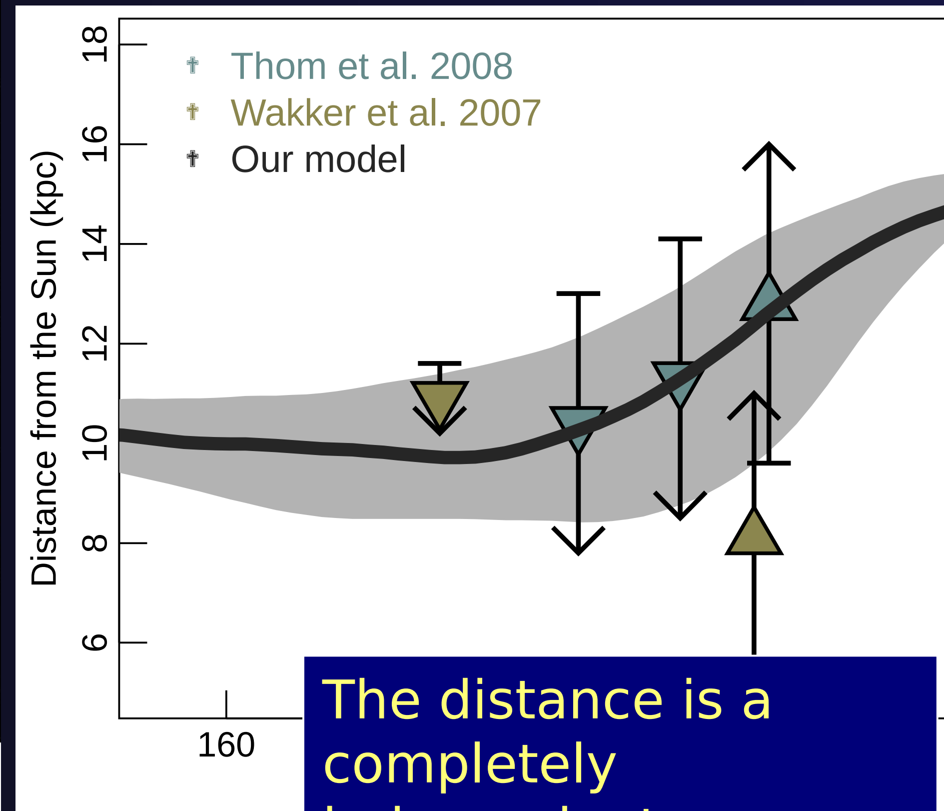


ternali, Marasco, Armillotta, & Marinacci 2015, MNRAS Letter, 447, 70

Origin & Location of Complex C



Distance from the Sun

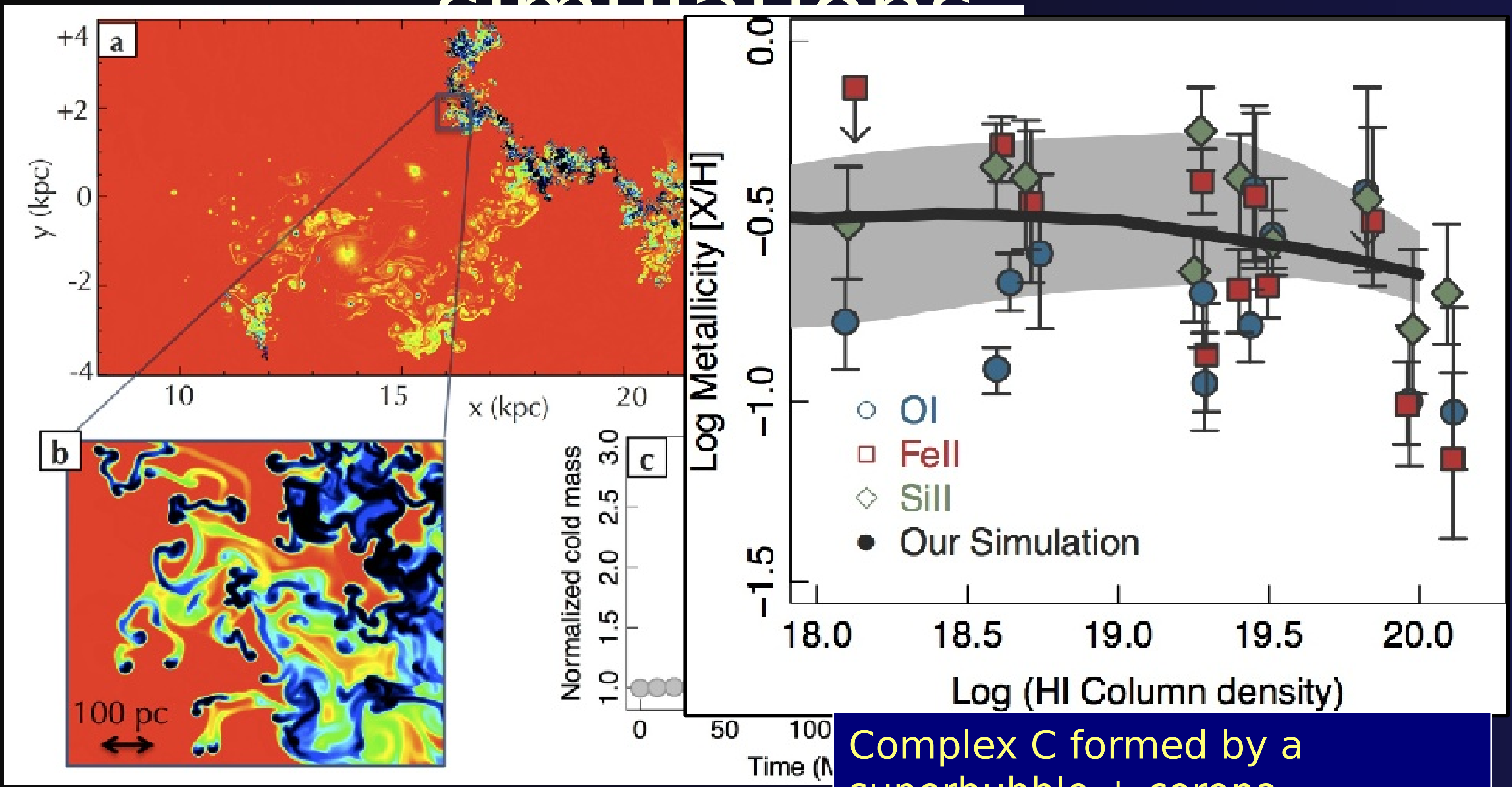


The distance is a completely independent confirmation

	v_0	R_0	δ_{arm}	t_0	Δt	t_{de}…	(seed)	(final)
	[km s^{-1}]	[kpc]	[kpc]	[Myr]	[Myr]	[Myr]	[$10^6 M_\odot$]	[$10^6 M_\odot$]
Best-fit	211	9.5	2.9	150	53	46	3.4	6.8

Ekin ~ 2 x 1054 erg

Hydrodynamical simulations



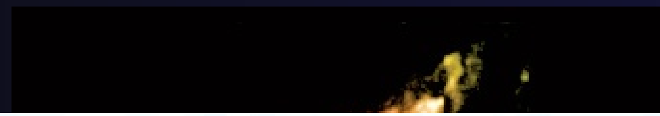
Average metallicity at the end: 0.27 Solar

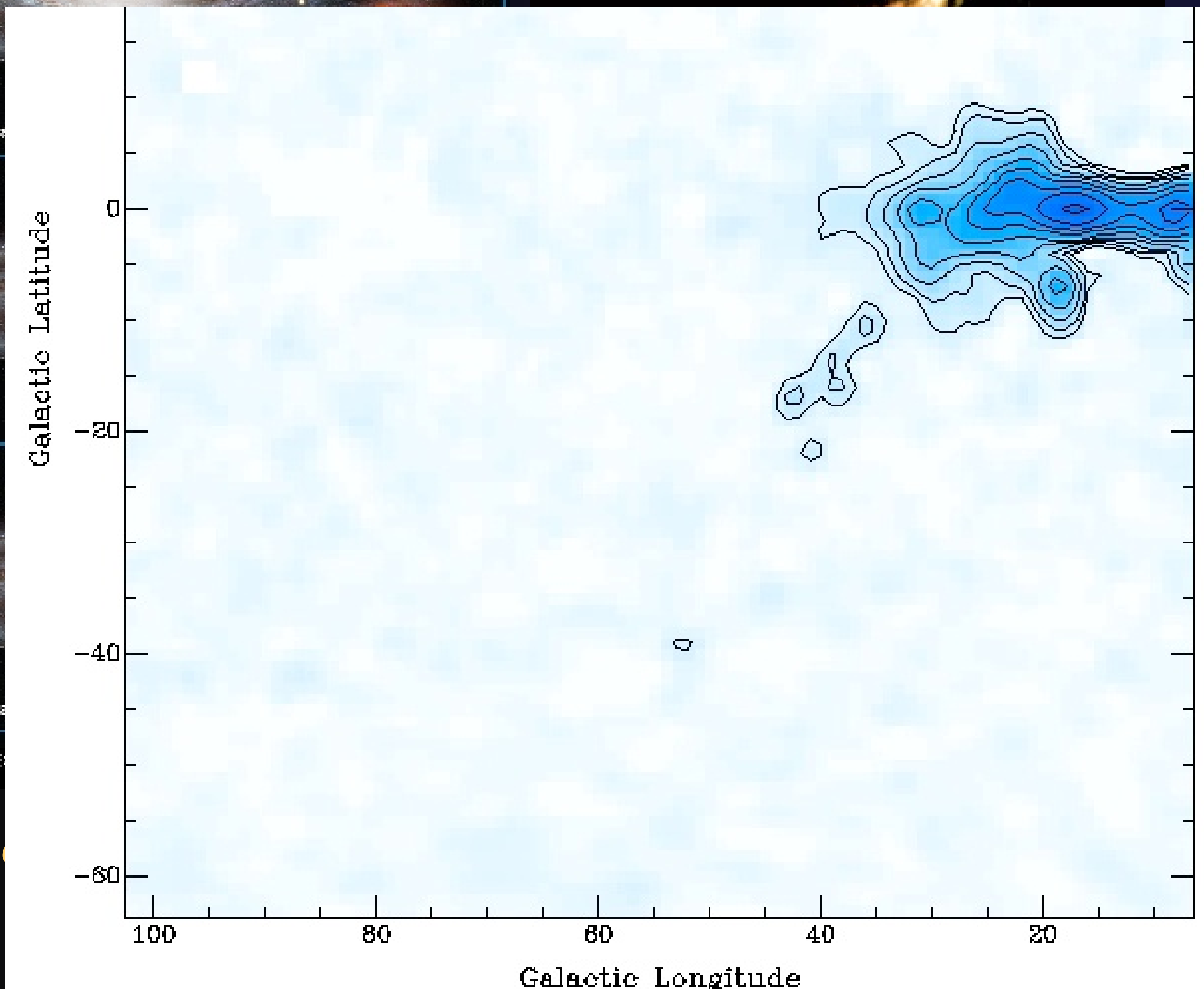
Compared to complex C: 0.1-0.3 Solar

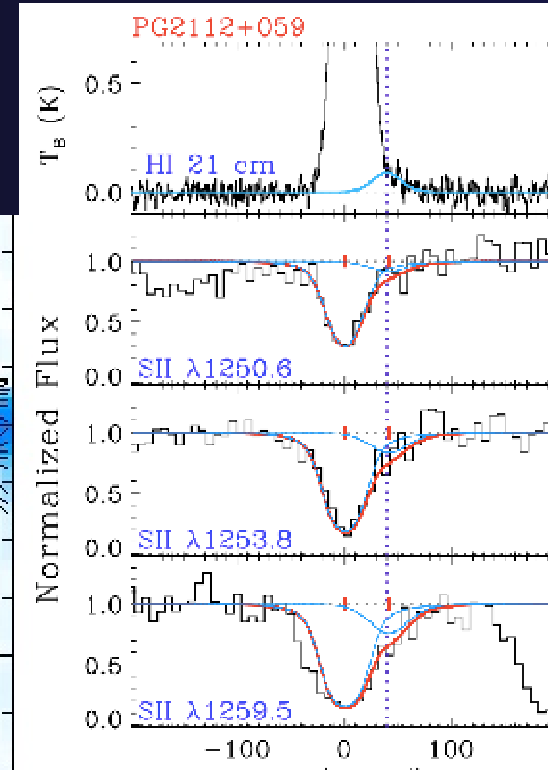
Complex C formed by a superbubble + corona condensation

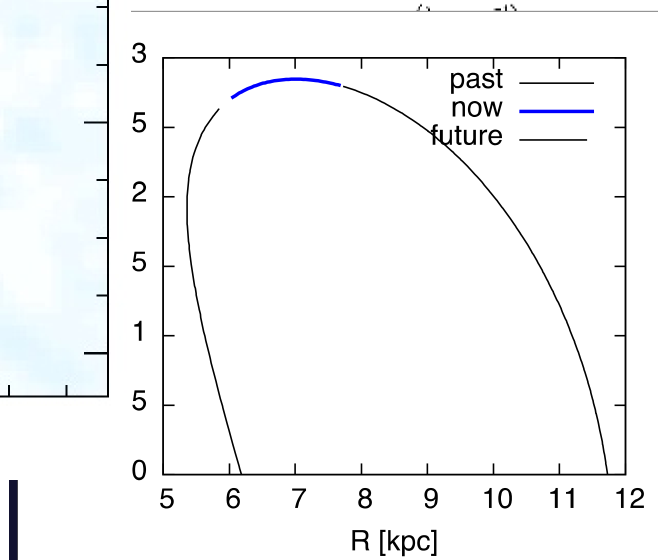
Local manifestation of fountain-driven accretion

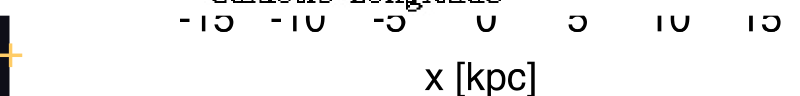
Smith cloud









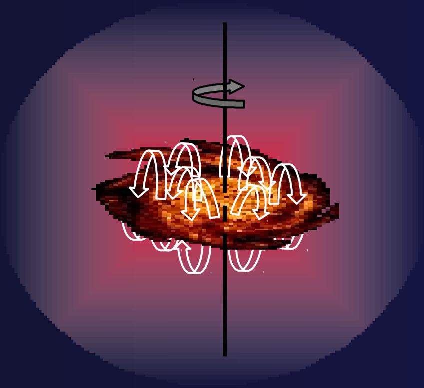


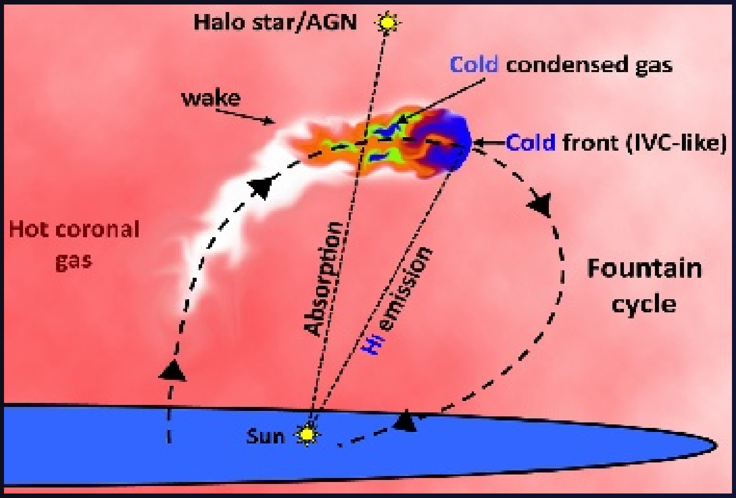
Fox (

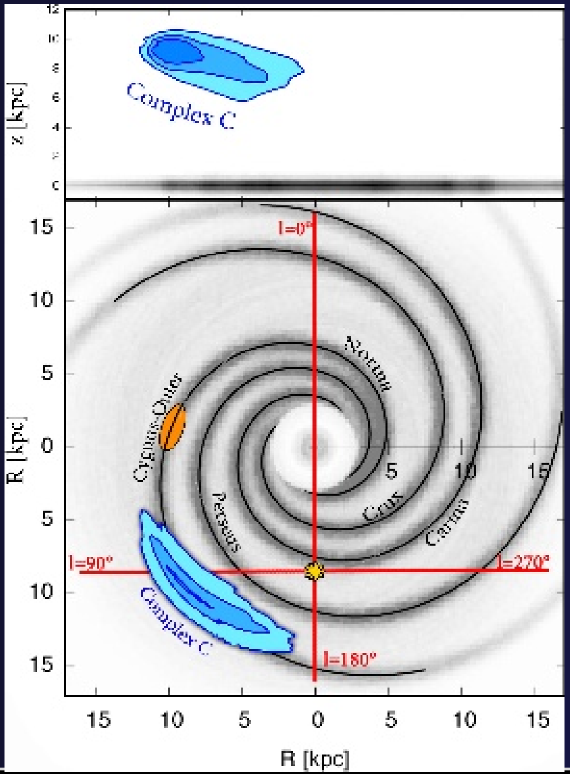
Marasco, Fraternali+

Conclusions

- Galactic fountain can cool the corona and feed the star formation in disc galaxies like the MW
- Local features like HVCs can form (condense) out of this non-linear perturbation of the corona
- Very good fit for the prototypical complex C, promising results for Smith cloud





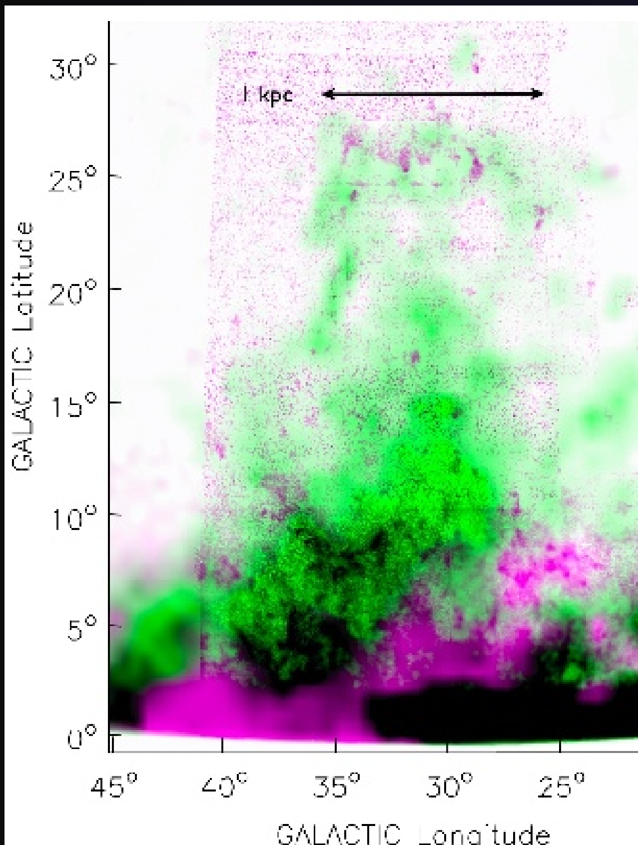



CROSSING THE RUBICON
The fate of gas flows in galaxies
https://sites.google.com/site/rubiconf2016
Santarcangelo di Romagna, Italy
5-9 September, 2016
INVITED SPEAKERS
Manda Banerji (IoA, UK)
Joel Bregman (Michigan Univ., USA)
Natascha Förster-Schreiber (MPE, Germany)
Joe Hennawi (MPIA, Germany)
Andrew King (Leicester Univ., UK)
Simon Lilly (ETH, CH)
Federico Marinacci (MIT, USA)
Raffaella Morganti (ASTRON, NL)
Kate Rubin (CfA, USA)
Jorge Sanchez-Almeida (IAC, Spain)
Joop Schaye (Leiden Obser., NL)
Francesco Tombesi (Goddard SFC, USA)
Sylvain Veilleux (Maryland Univ., USA)
Jessica Werk (UC S. Cruz, USA)

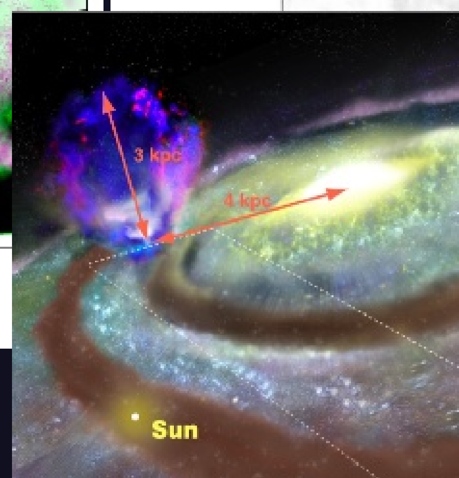
Thanks

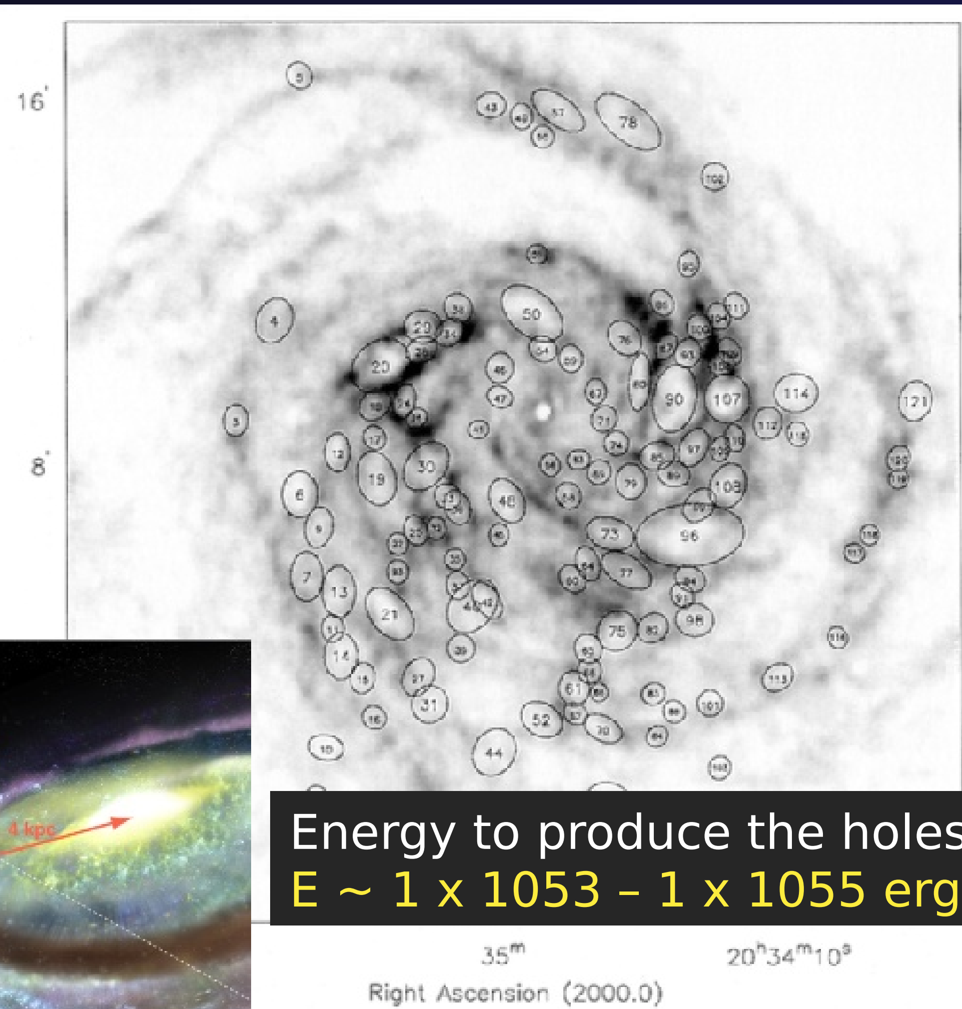
Ophiucus superbubble

Purple HI
Green Halpha



Pidopryhora et al. 2007, ApJ

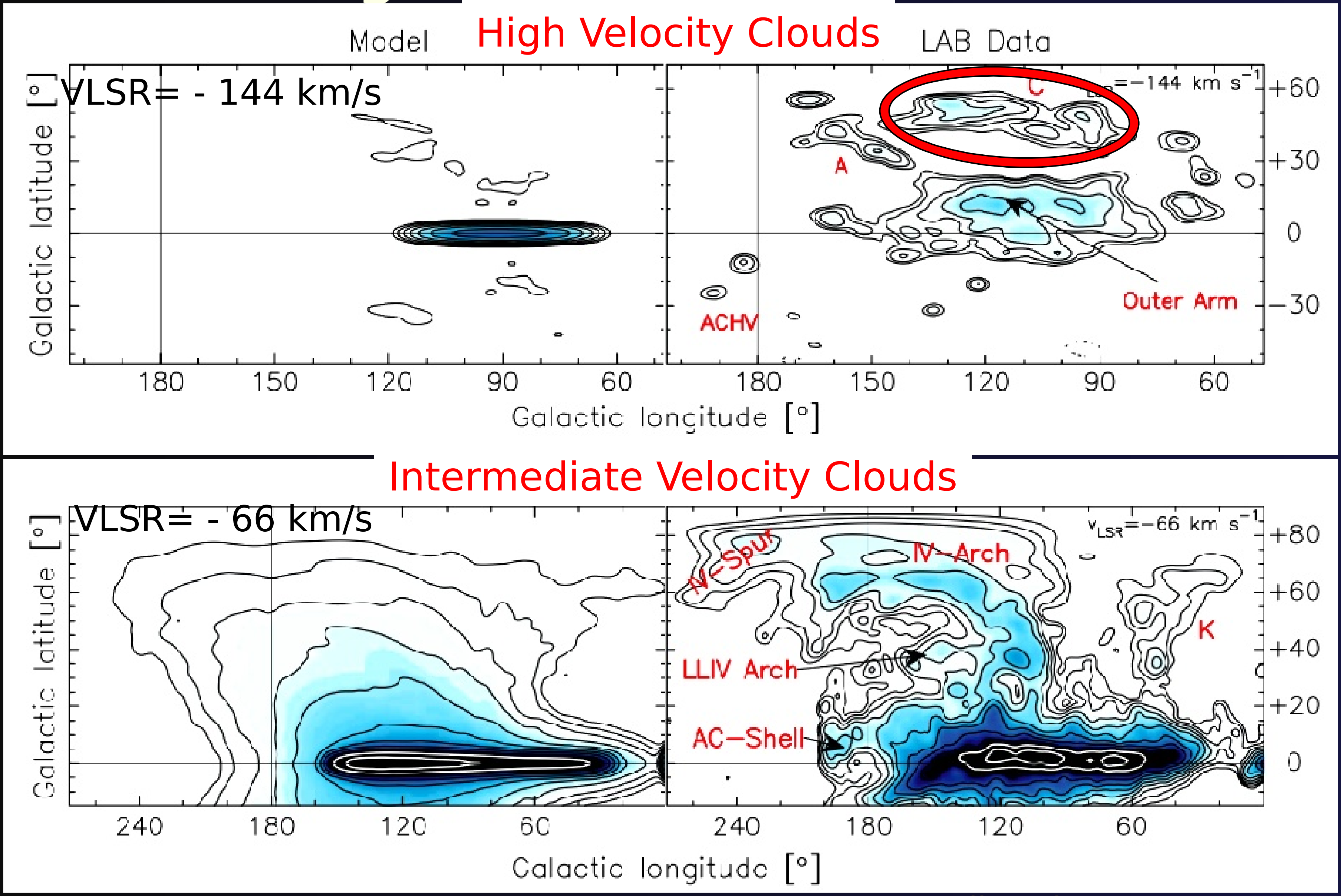




Energy to produce the holes:
E ~ 1 x 1053 – 1 x 1055 erg

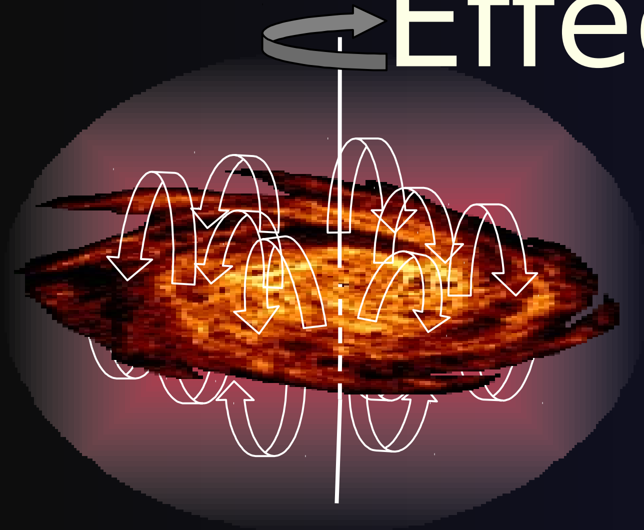
Boomsma et al. 2008, A&A

Our galactic fountain model



Marasco, Fraternali & Binney 2012, MNRAS

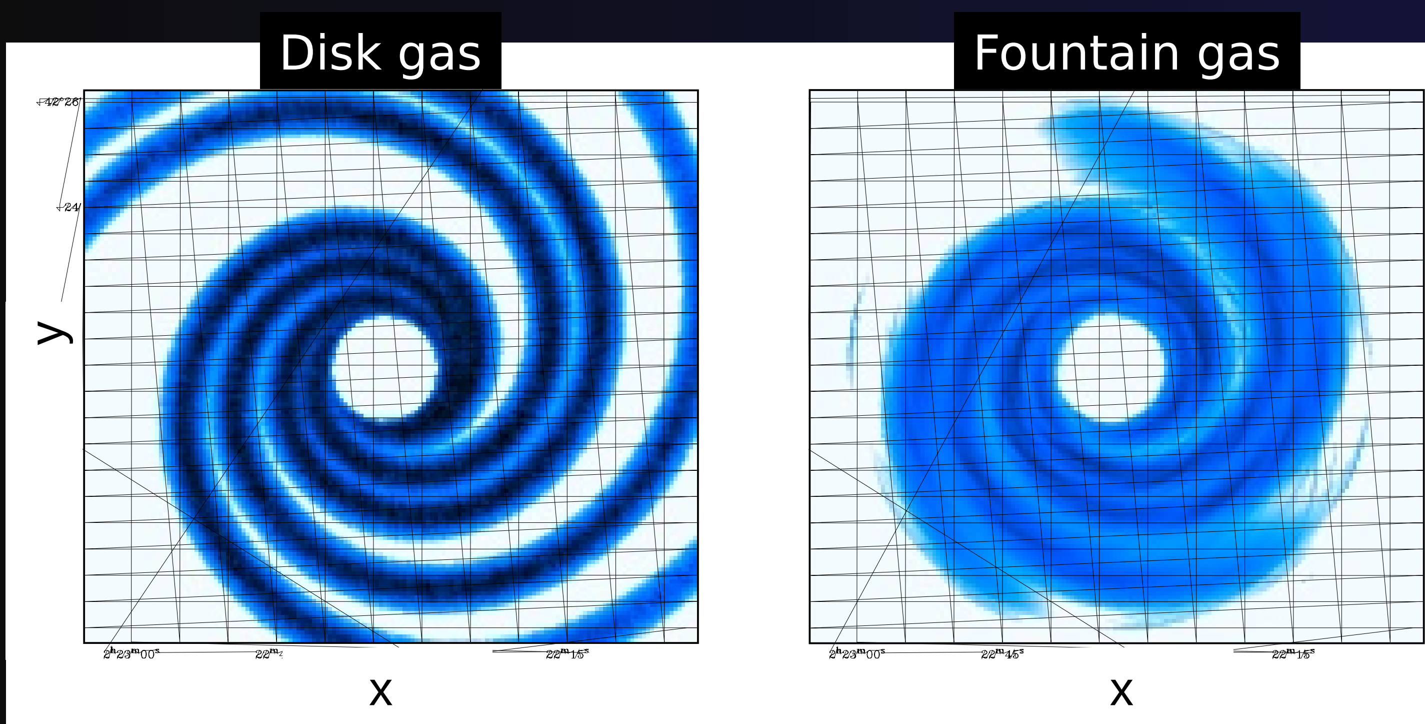
Effect of spiral arms



Two limitations of our model:

1. *Axisimmetry*
2. *Average ejection velocities*

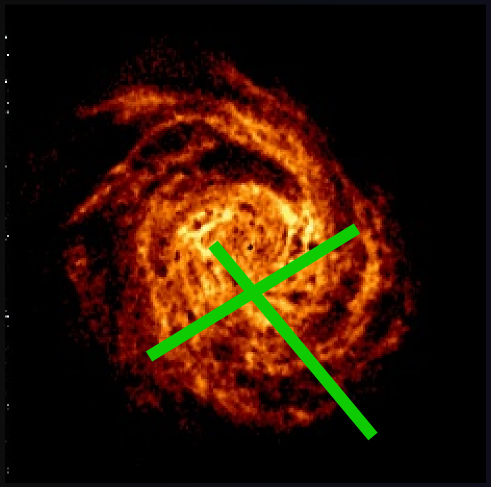
We introduced spiral arms



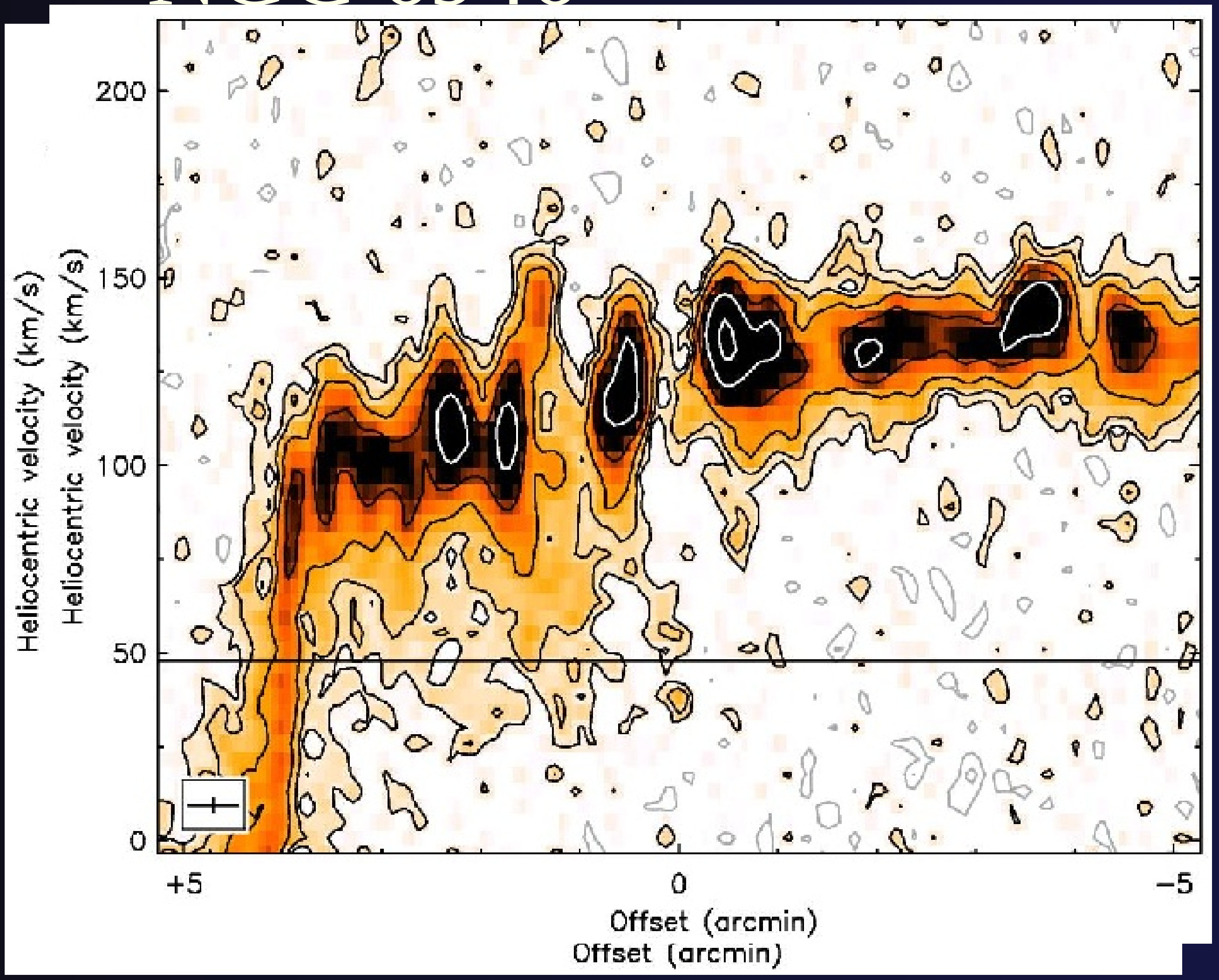
Global model unchanged!

Best-fit Accretion Rate ~ 2 $M_\odot yr^{-1}$

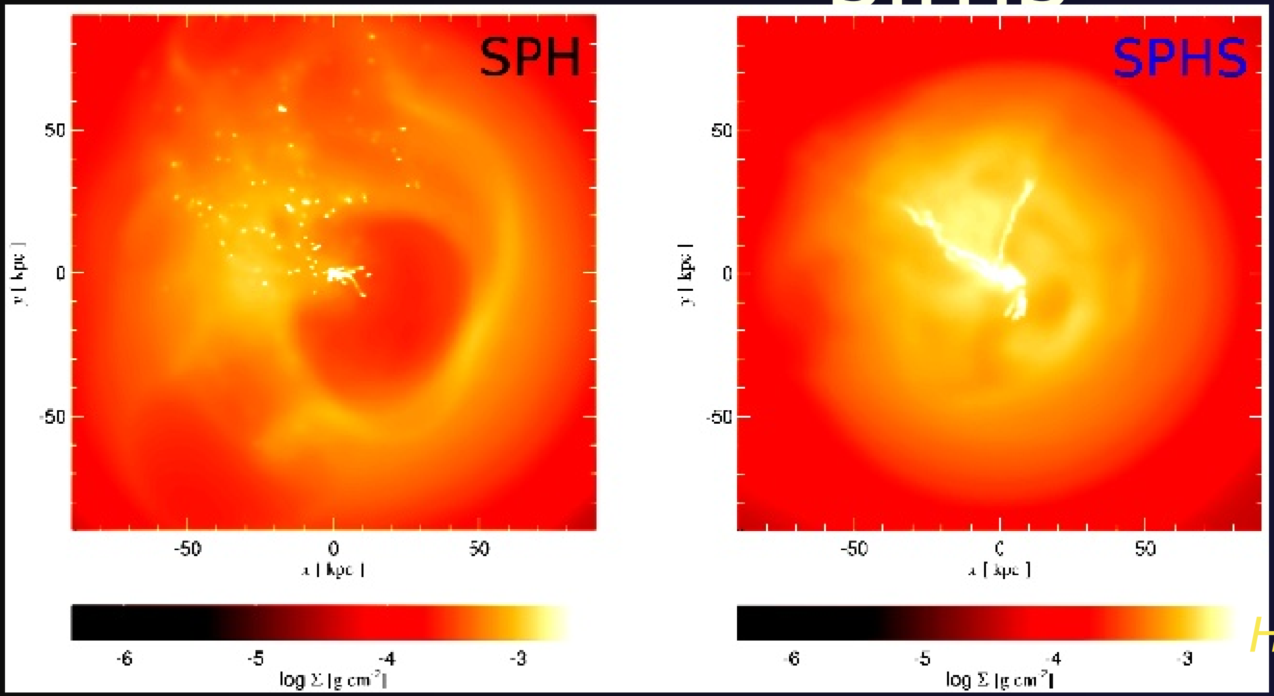
NGC 6946



Boomsma et al. 2007



SN-driven accretion in other sims



Modified SPH

No formation of clumps

"Cold gas condenses from the halo at the intersection of supernovae-driven bubbles. This positive feedback feeds cold gas to the galactic disc directly fueling SF."

Hobbs et al. 2013, MNRAS

MaGICC - GASOLINE

Halos enriched by galactic fountain

Gas in the fountain cycle comes back to the disk more metal poor!

Brook+12, Brook+13

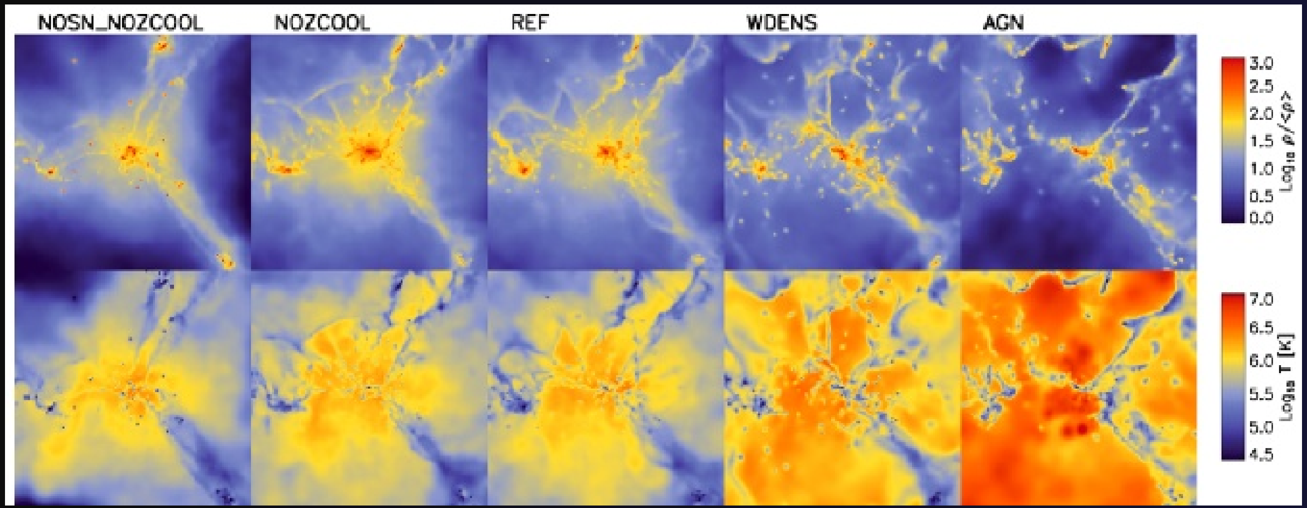
Impact of galactic fountain on disc evolution

1. Corona-disc interface

2. Global process: supernova-driven accretion

3. Local process: formation of condensed clouds
   - Origin of the high-velocity cloud complex C

Positive feedback is there

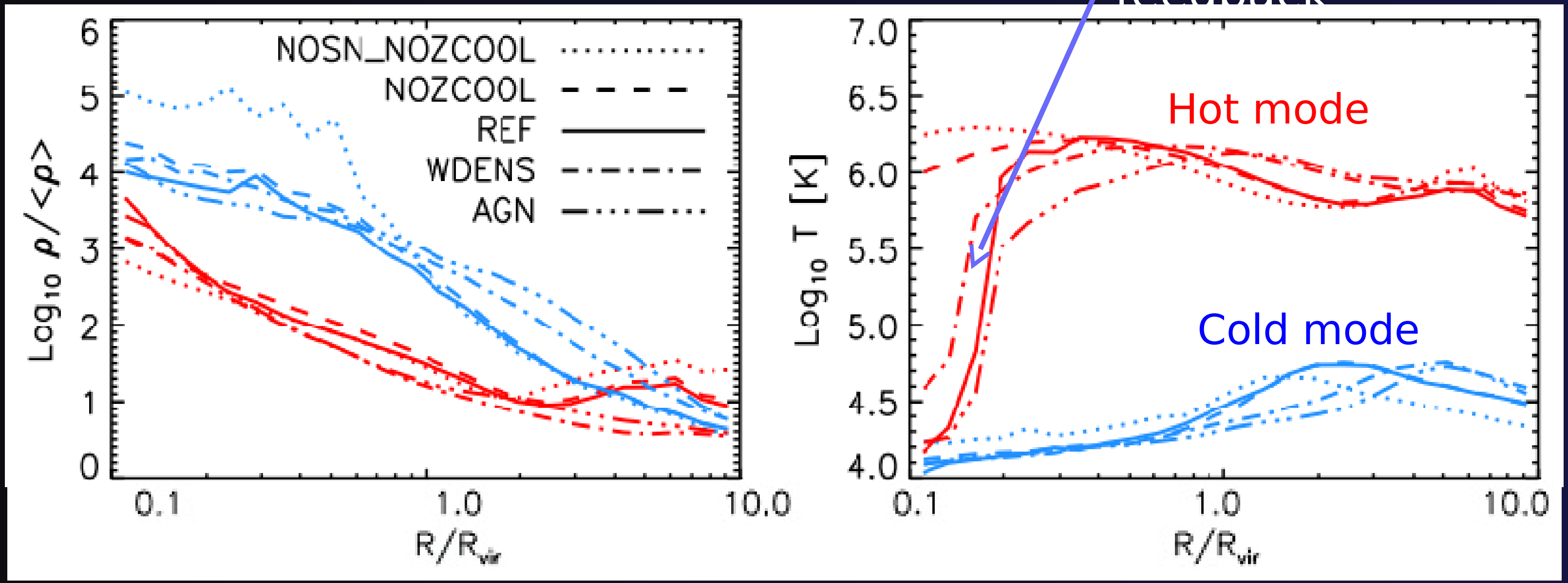


z=2

Cooling induced close to galaxies by metals ejected by feedback

OWLS

GADGET-3

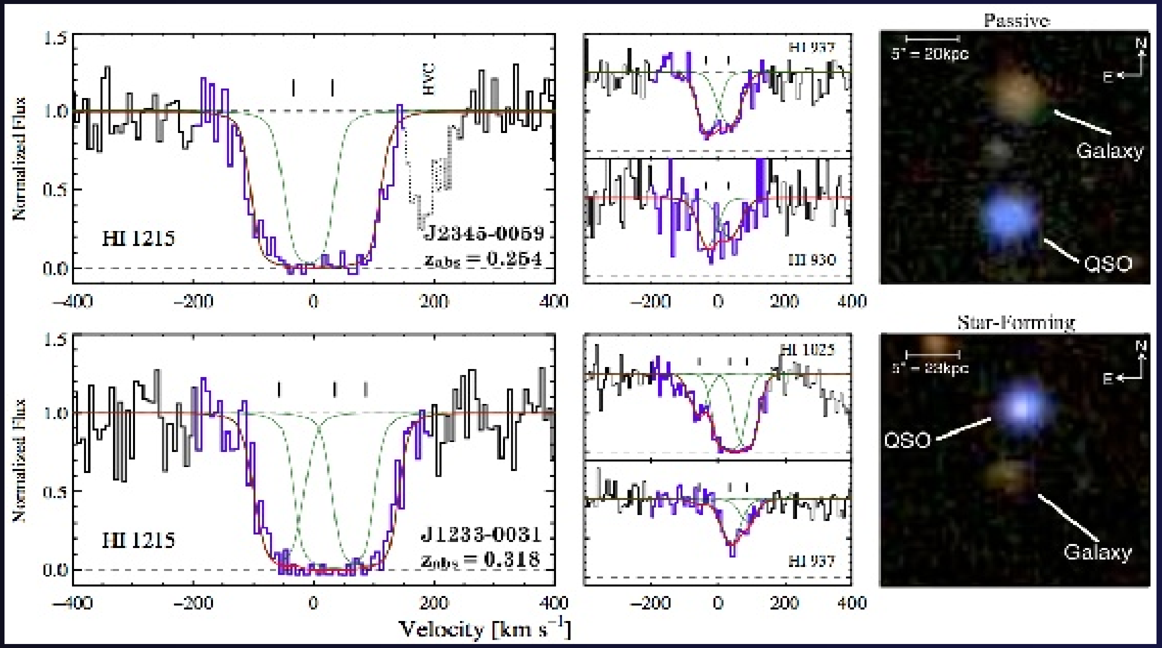


van de Voort & Schaye 2012

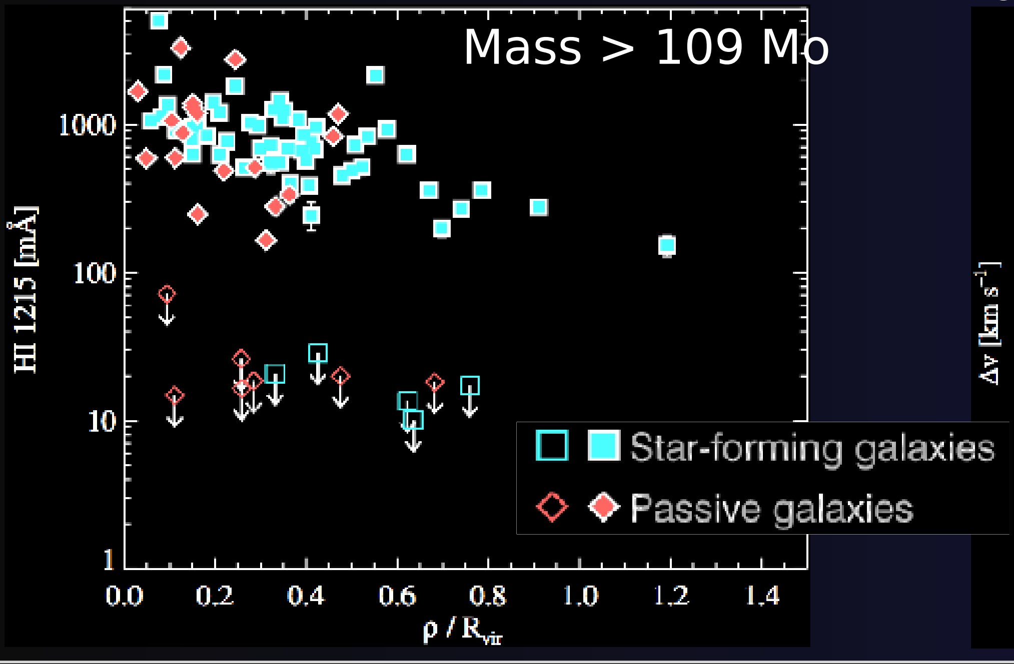
Lyα absorbers

HST/COS data

Thom+ 2012, ApJL

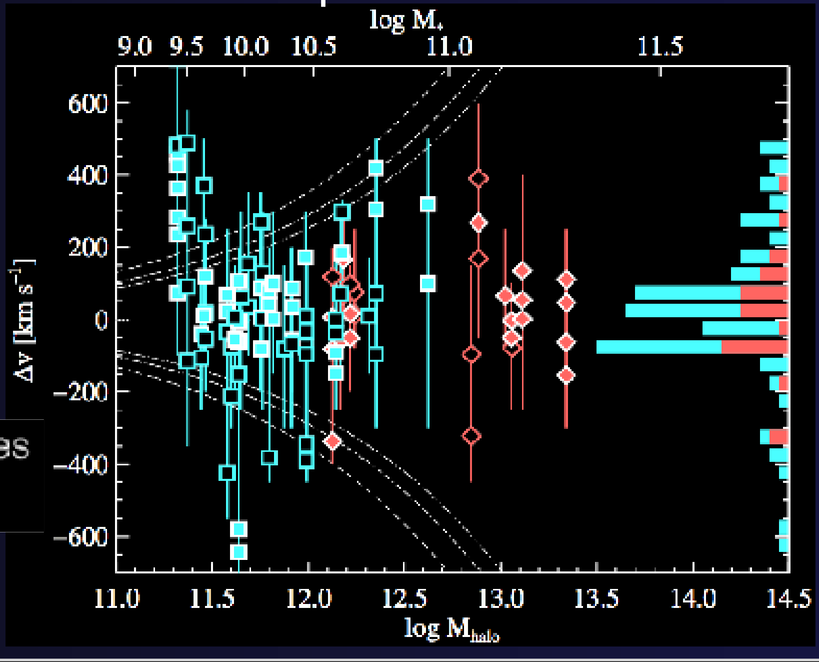


Impact parameters



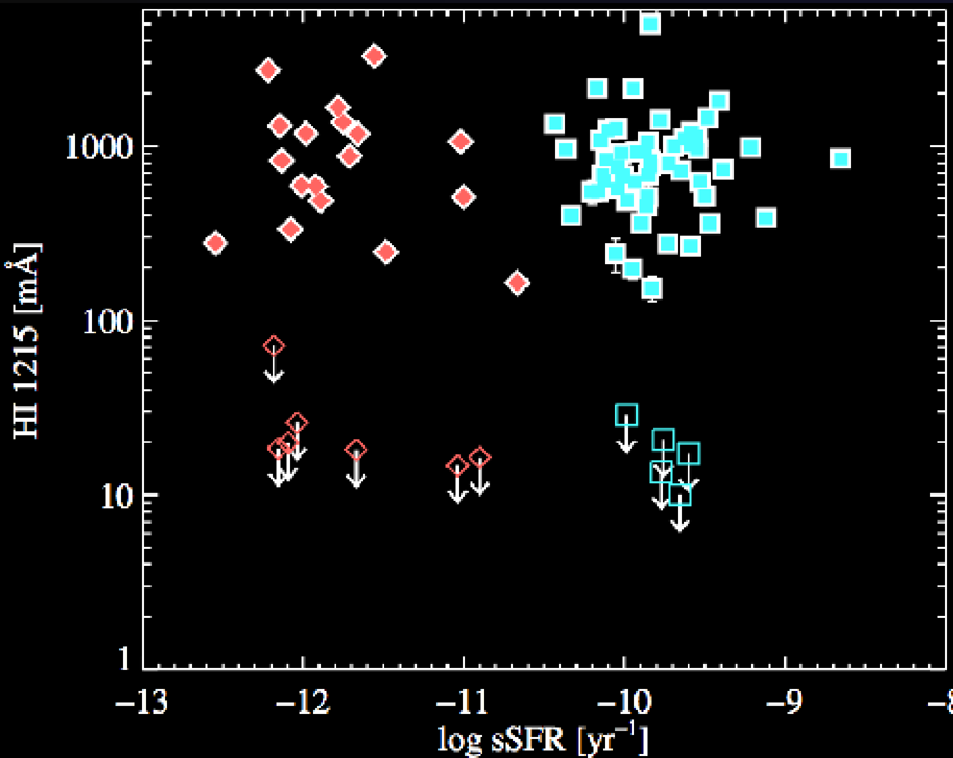
Mass > 109 Mo

Bound to the potential wells



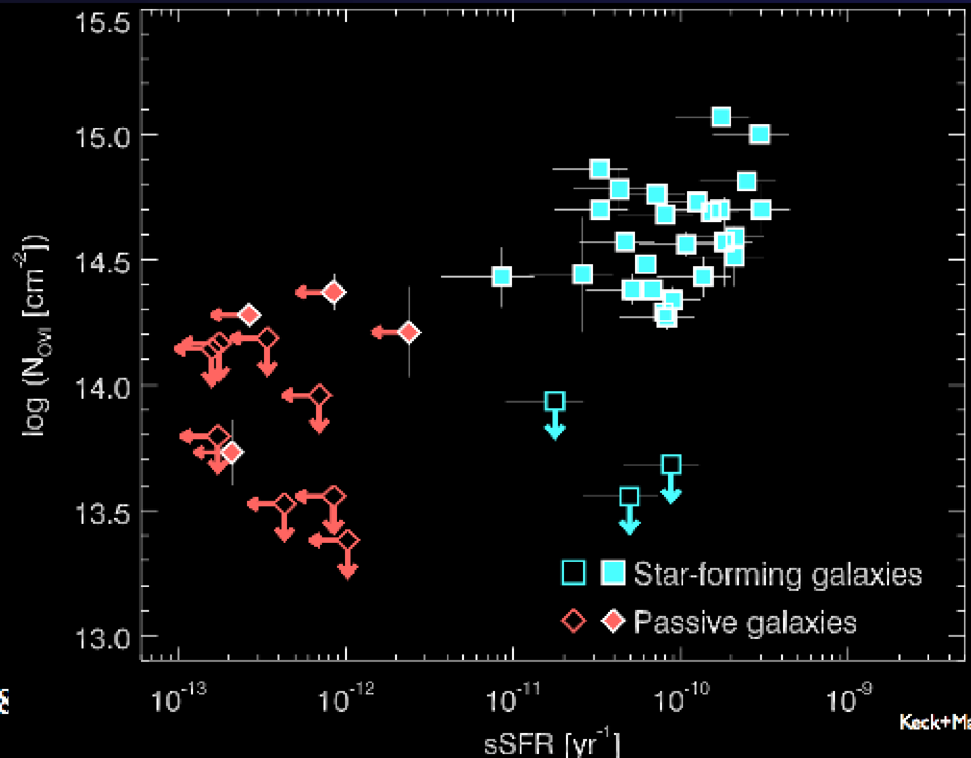
Early types vs star-forming

Cold gas (log(T)<5)



Thom+ 2012, ApJL

Hot gas (log(T)~5.5)



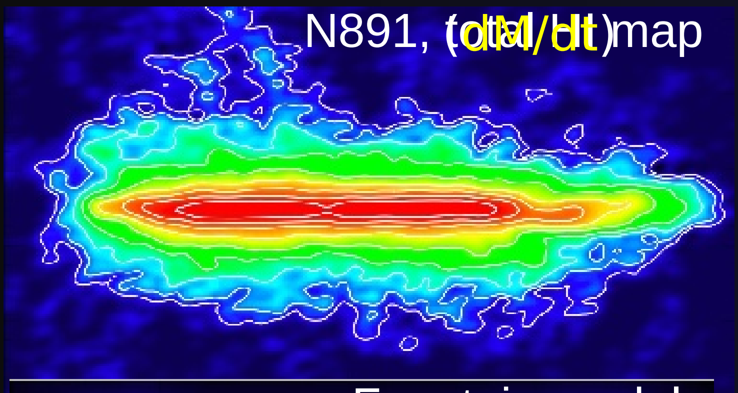
Tumlinson+ 2013

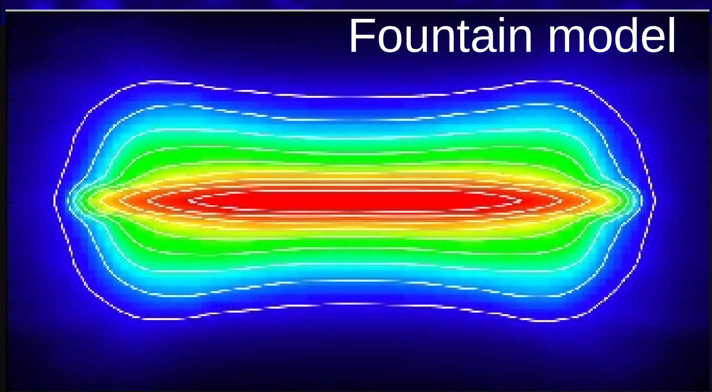
Werk+ 201

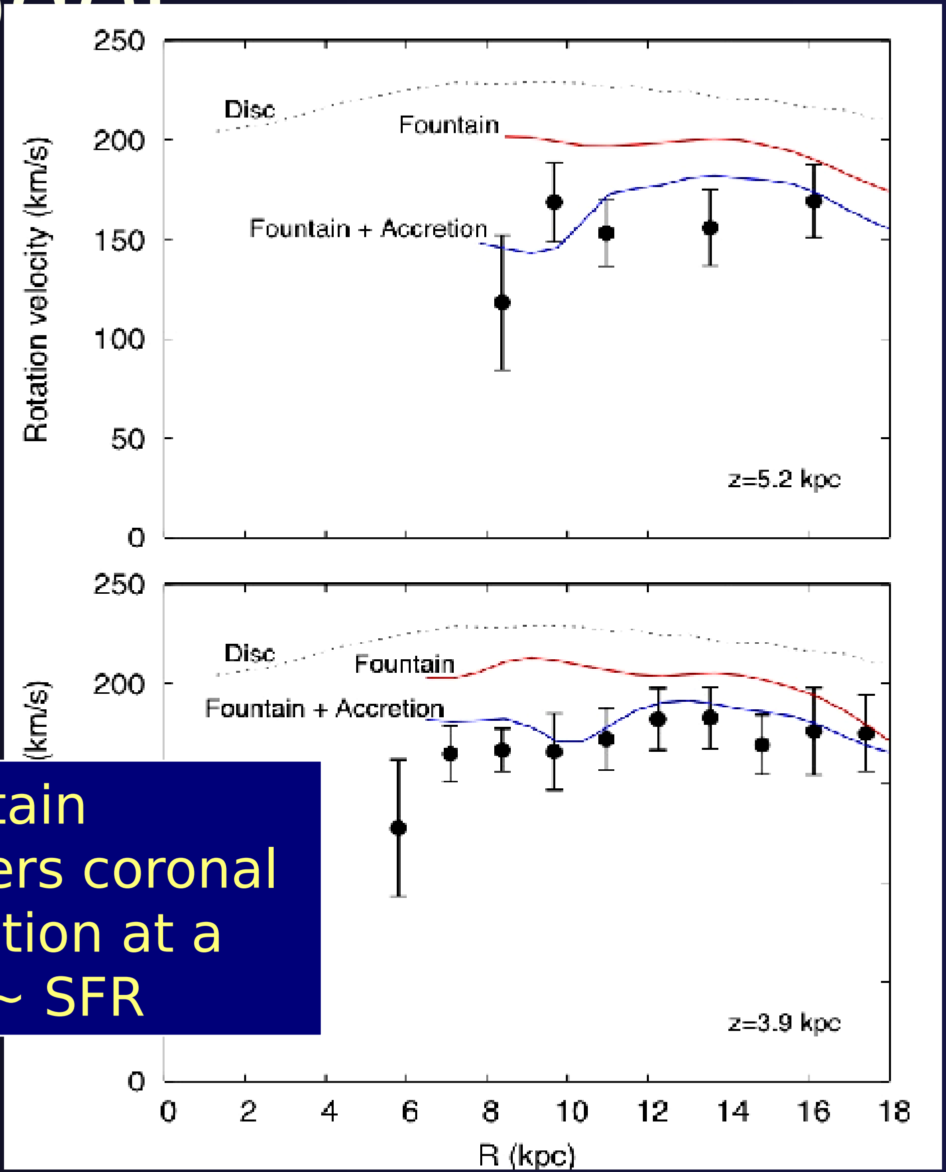
Is this *cold* gas used for star formation?

Fountain-driven accretion model

1. kick velocities (vk)
2. Ionised fraction (fion)
3. Accretion rate (dM/dt)







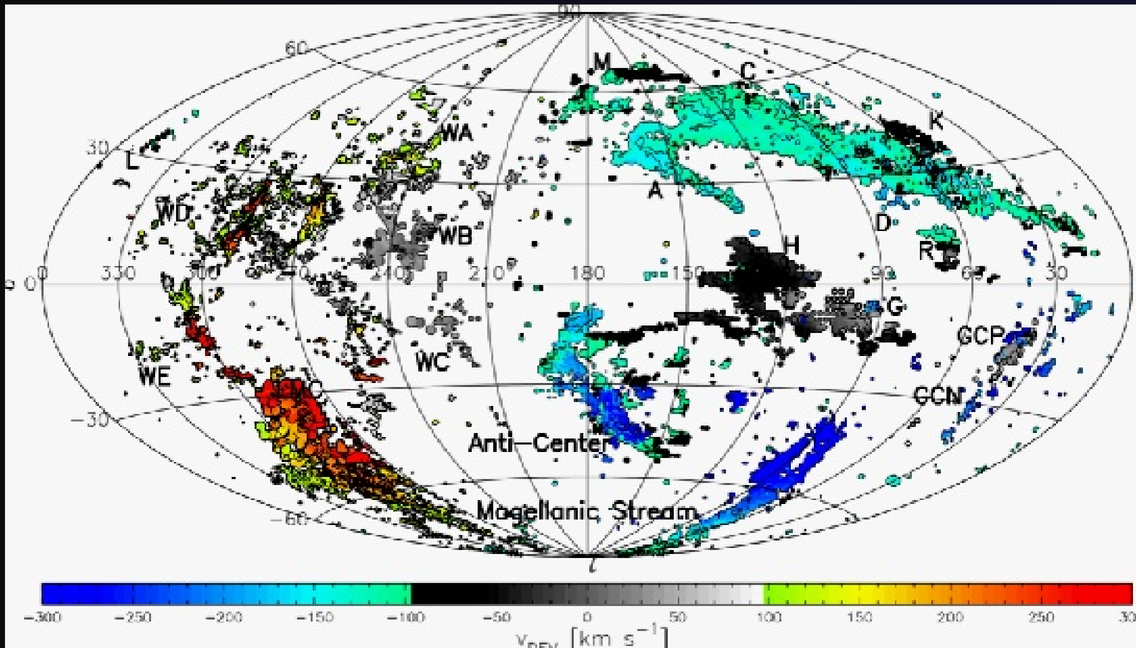
Fountain triggers coronal accretion at a rate ~ SFR

Best-fit Accretion Rate ~ 3 M☉yr-1

Compare to SFR ~ 4 M☉yr-1

Fraternali & Binney, 2008

HI High Velocity Clouds



Typical Distances: ~10 kpc

h~few-10 kpc

Z~0.1-0.4 $Z_\odot$

M<107 $M_\odot$

Wakker et al. 2007, 2008; Tripp et al. 2003

Accretion from High Velocity Clouds

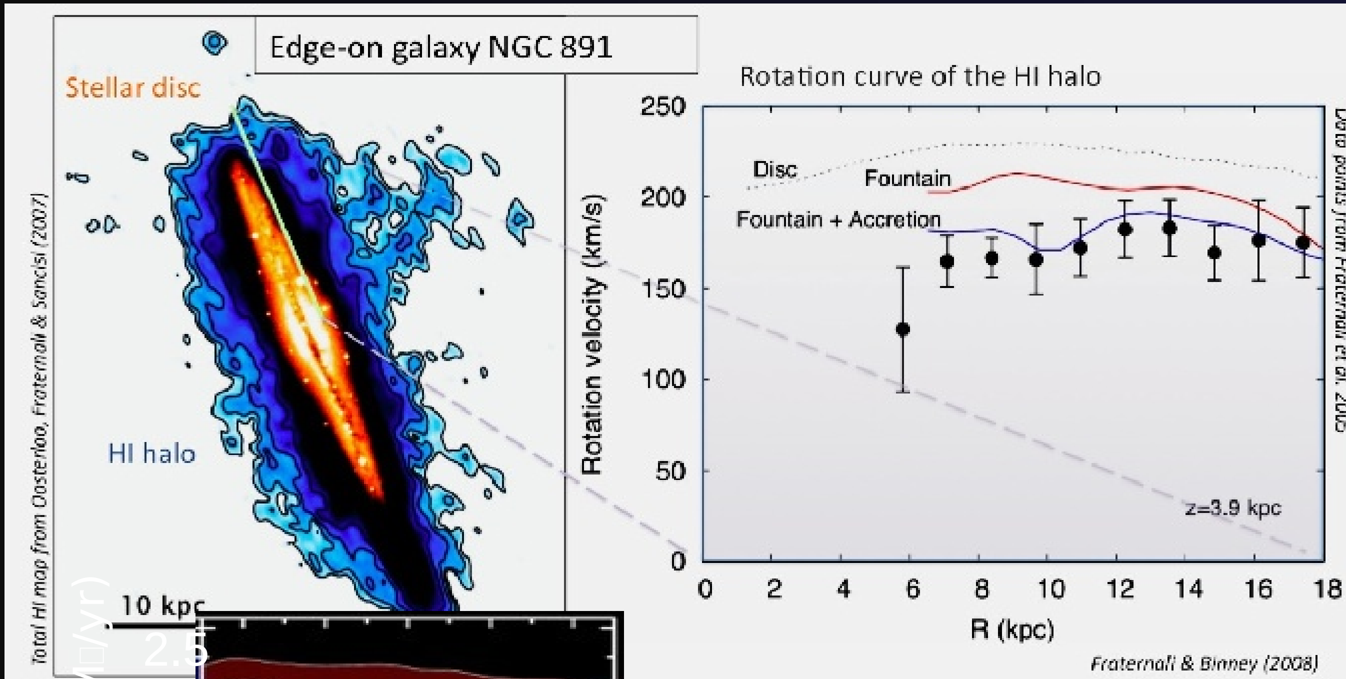
→ ~ 0.08 $M_\odot$/yr   Includes He and factor 2 of ionised gas!

HI HVCs cannot feed SF

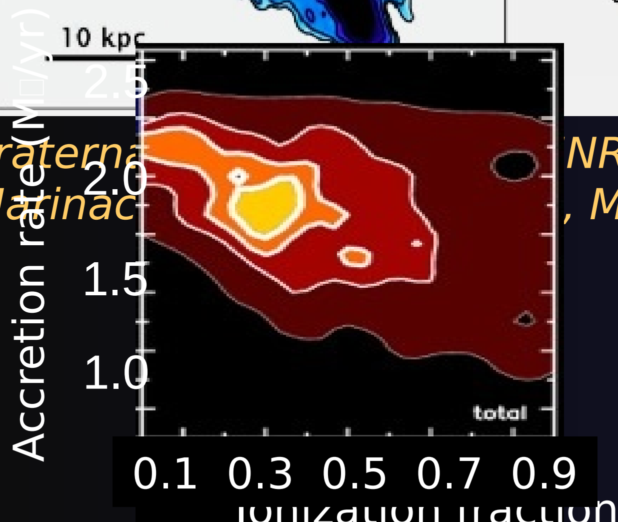
Putman, Peek, Joung 2012, ARA&A

Implications for galaxy evolution

Global fountain



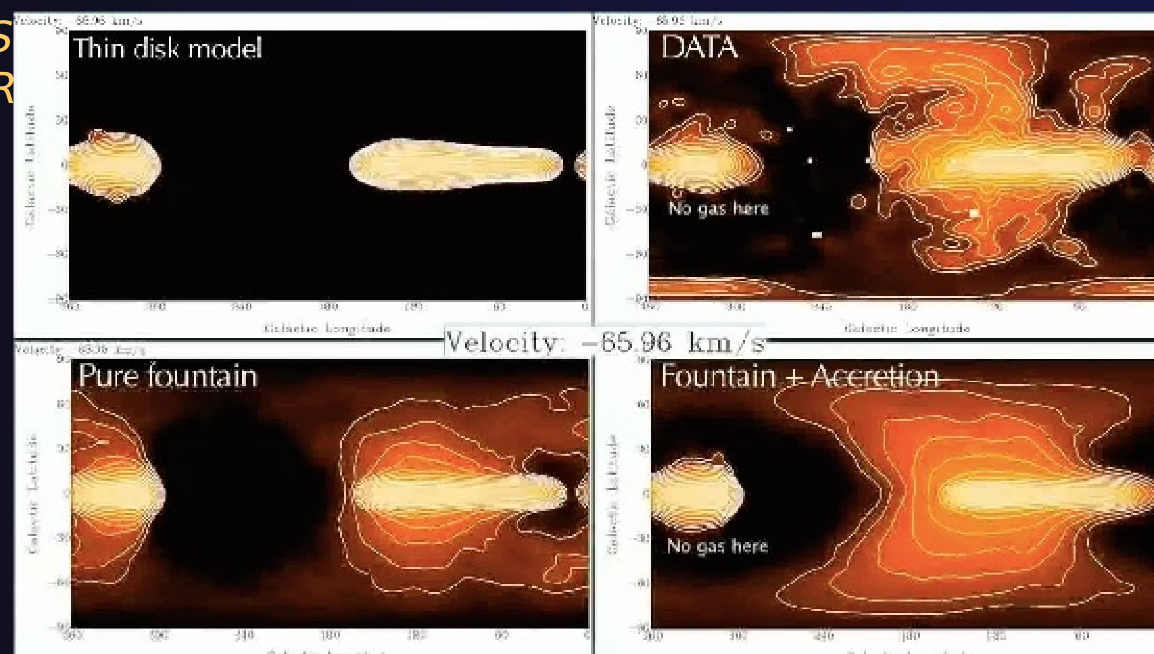
Fraterna... NRAS
Marinac... , MNR



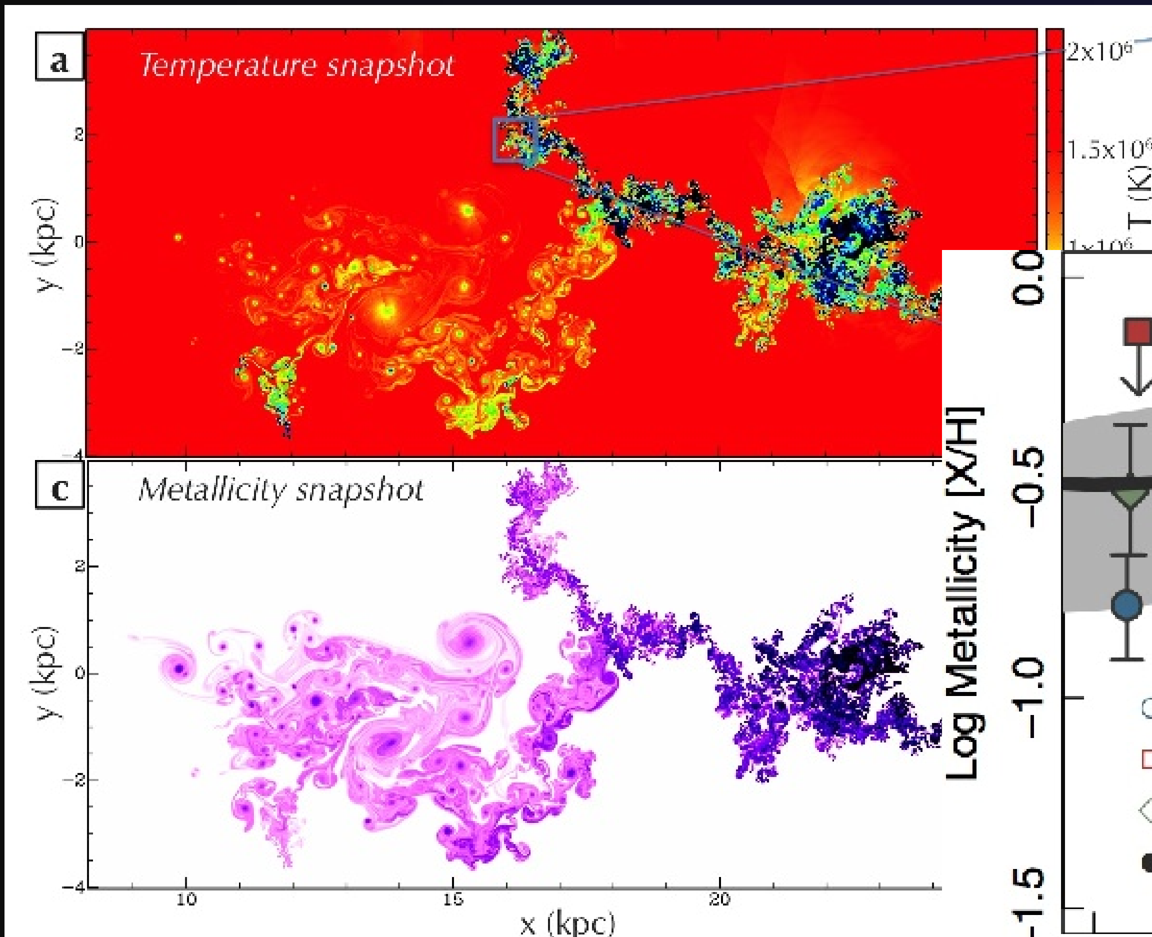
Best-fit Accretion Rate ~ 2 M□yr-1

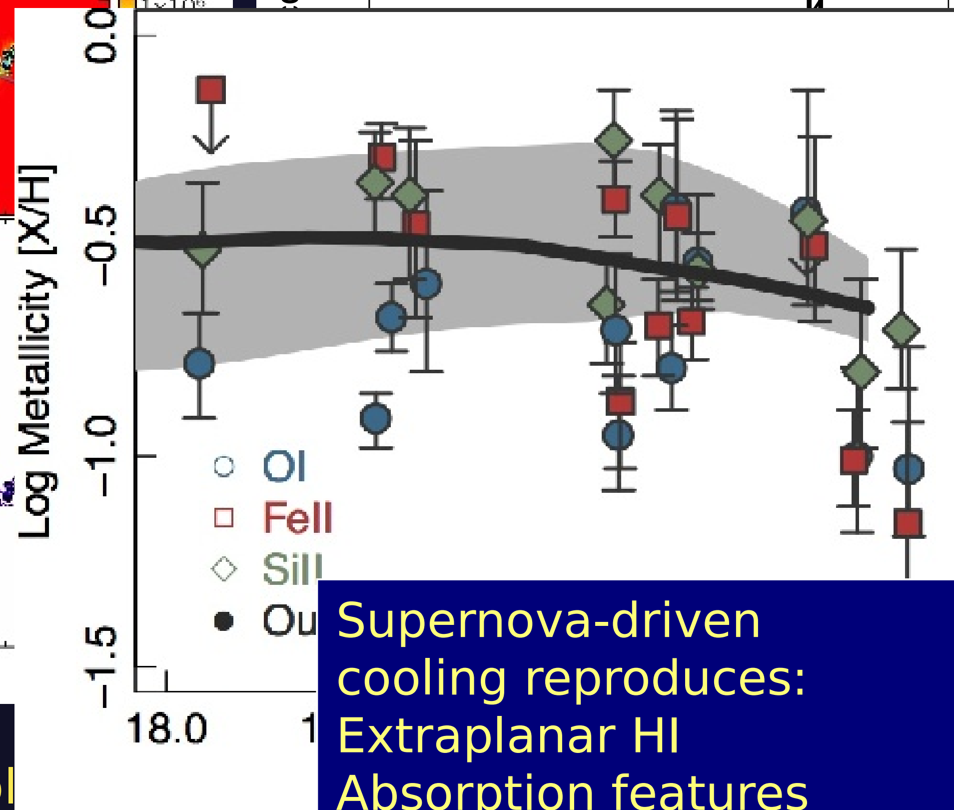
Compare to SFR ~ 1-3 M□yr-1

Marasco, Fraternali+ 2012, MNRAS



Metallicity



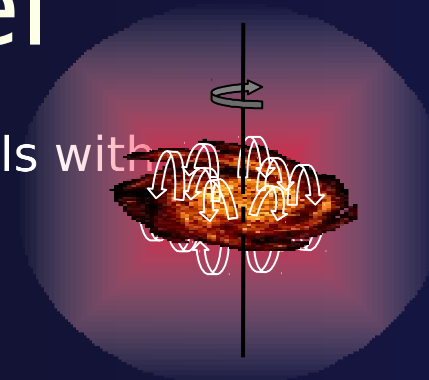


Supernova-driven cooling reproduces:
Extraplanar HI
Absorption features
And even HVCs

Average metallicity at the end: 0.27 Sol

Compared to complex C: 0.1-0.3 Solar

Galactic fountain model

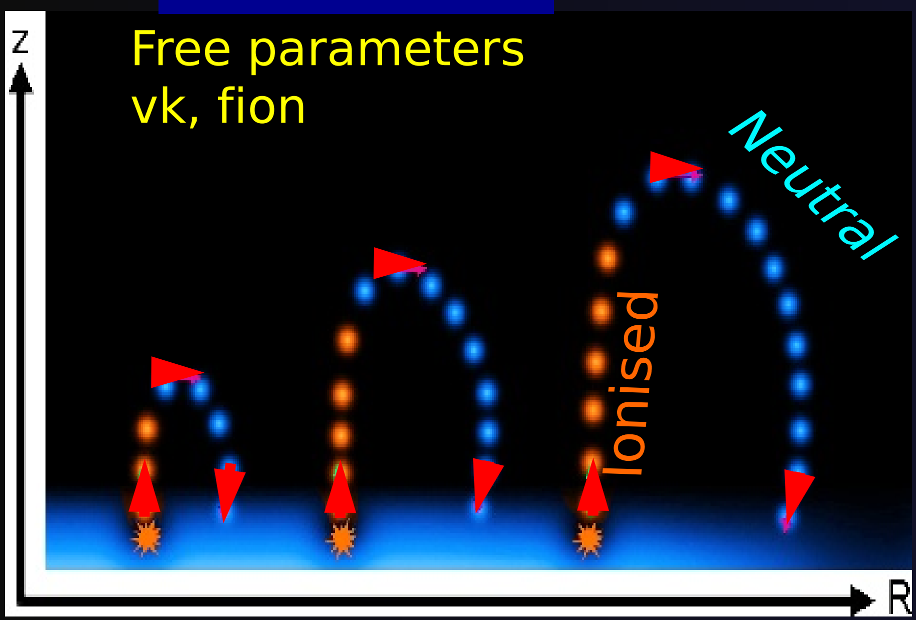


Building of several model cubes -> minimization residuals with LAB

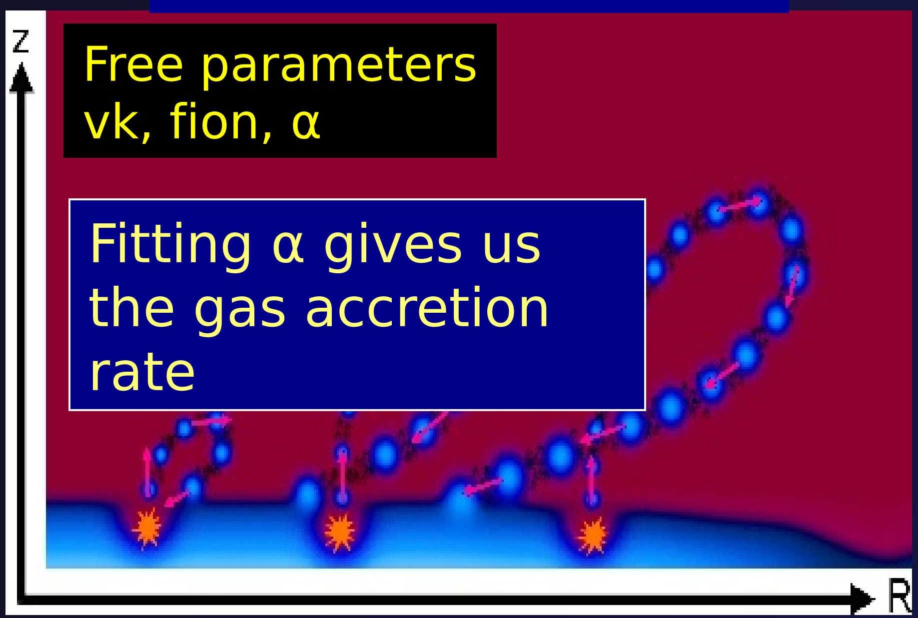
We fit:
1. kick velocities (vk) → scaleheight
2. Ionised fraction (fion) → vertical motions
3. Accretion coefficient (α) → radial motions

$$\dot{m} = \alpha m$$

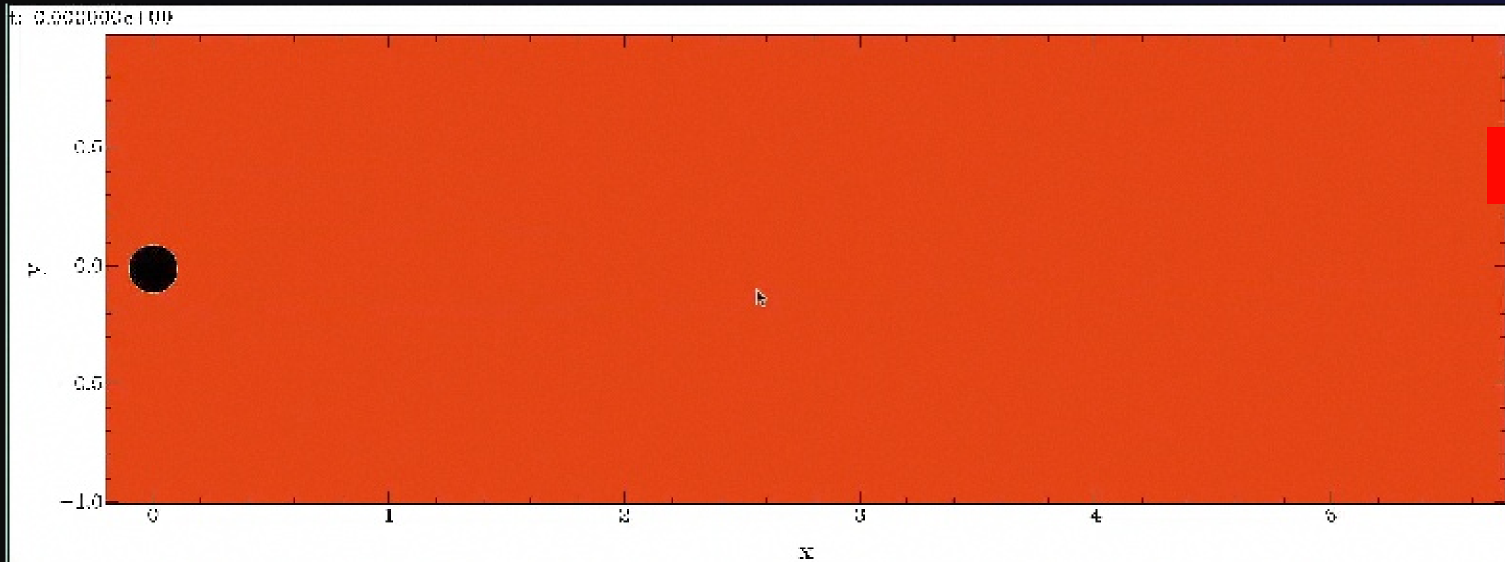
Pure fountain



Fountain + accretion



The effect of thermal conduction



Only cooling

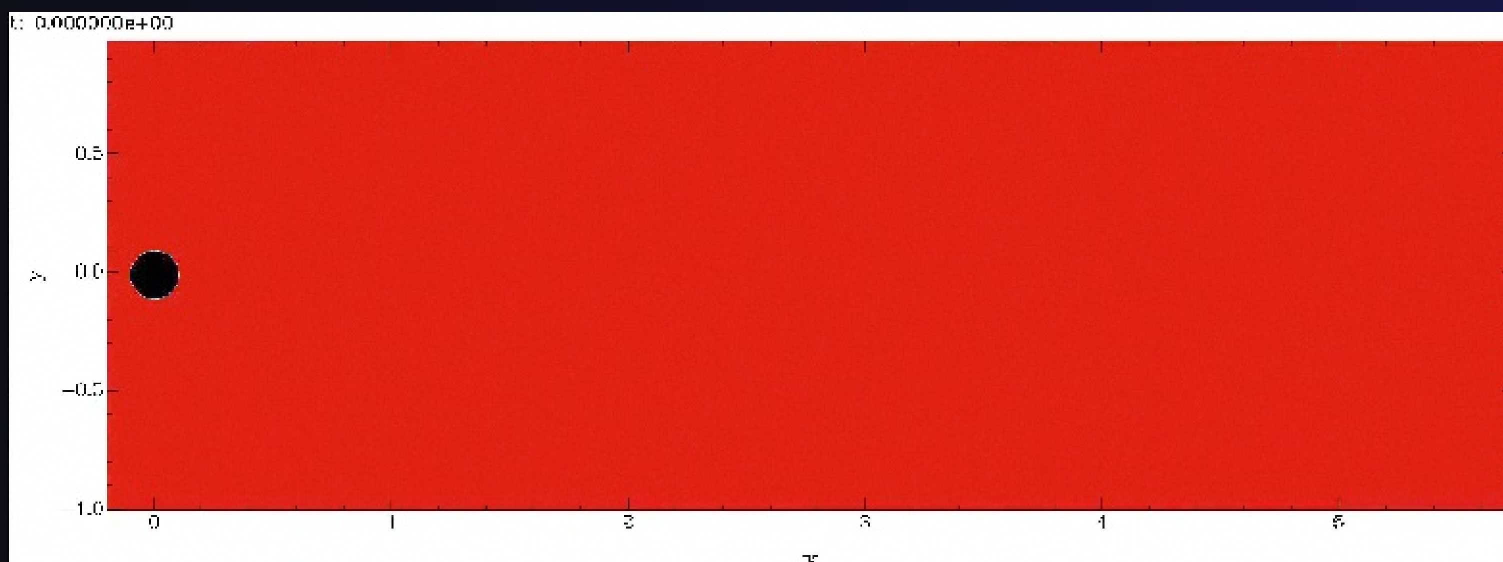
Tcorona=2x106

Zcorona=0.1 Z

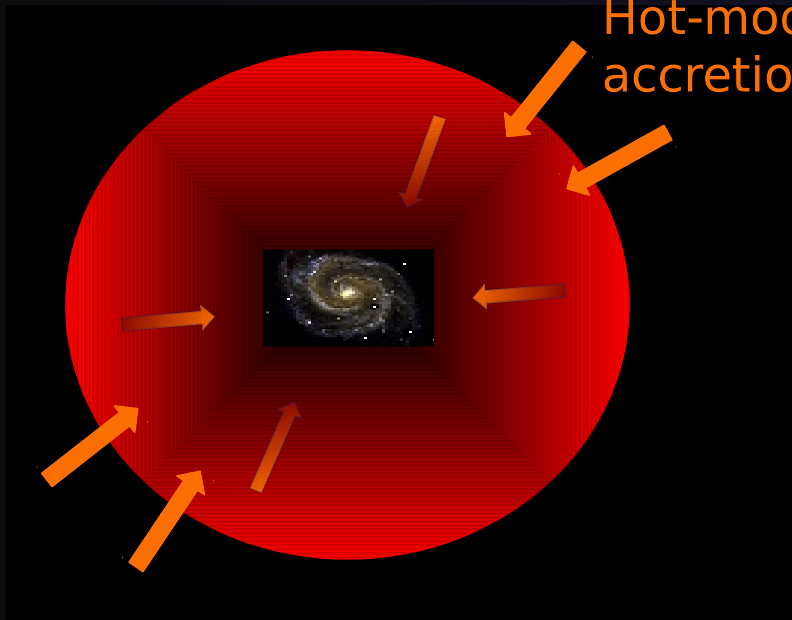
Zcloud=1 Z

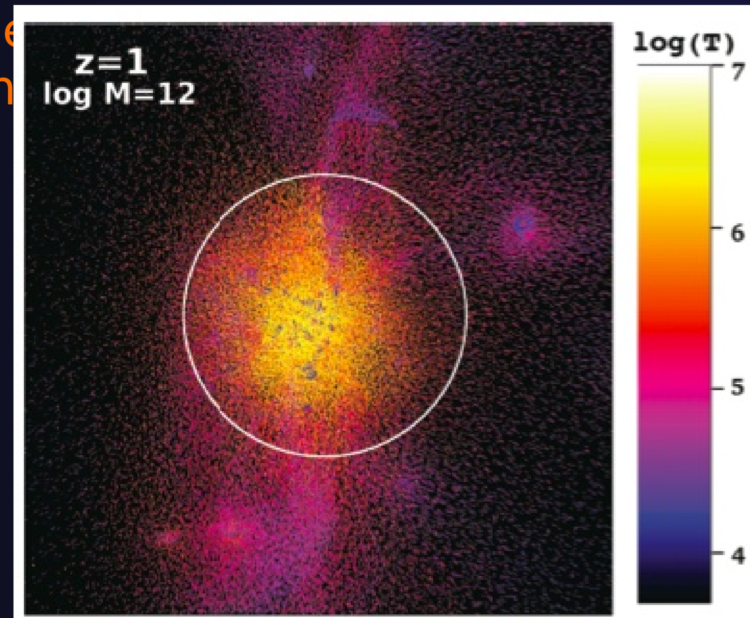
Cooling & thermal conduction

$$\mathbf{F}_{\rm cond} = f \times \kappa_{\rm Sp} T^{5/2} \nabla T$$



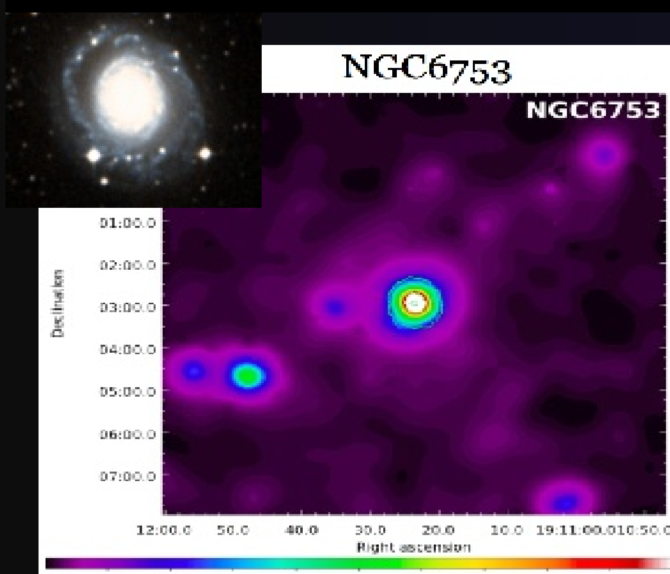
Galactic coronae

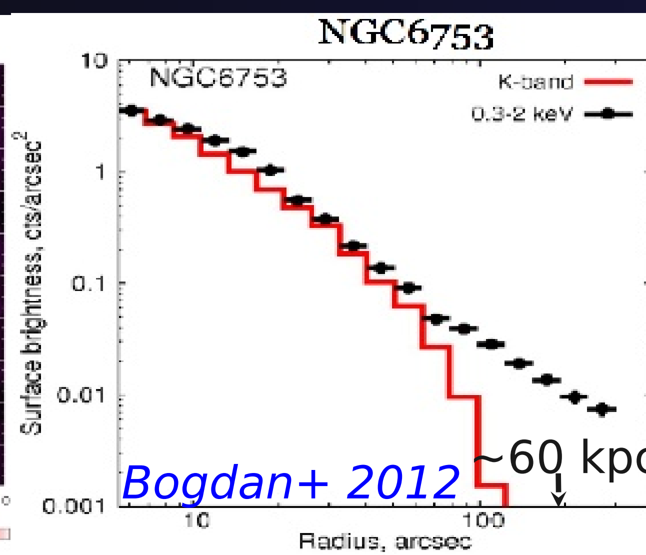




Keres+ 2009 Hot-mode accretion. Similar to classical theory (e.g. *White & Rees 1978*)

& Bregman 2012
Dai+ 2012, Anderson+ 2013



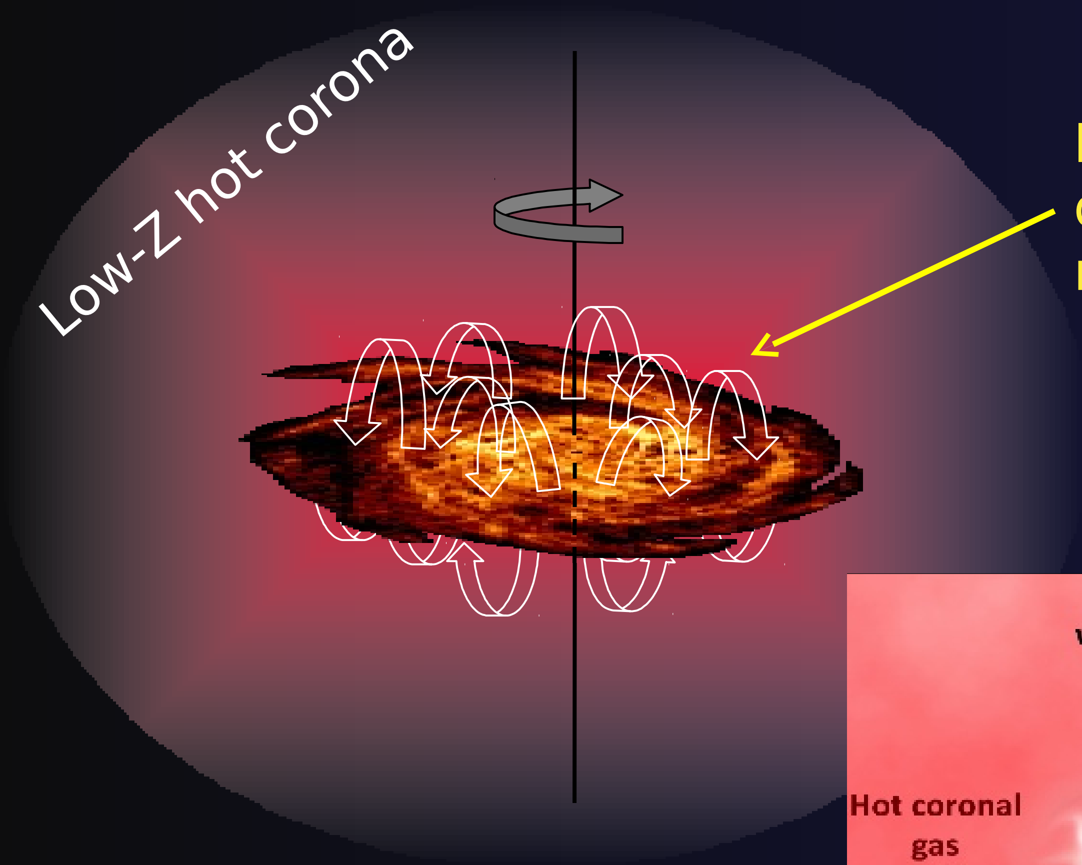


MW *Miller & Bregman+ 2013, 2015; Gatto+13*

Mass corona ~ 10-50% missing baryons

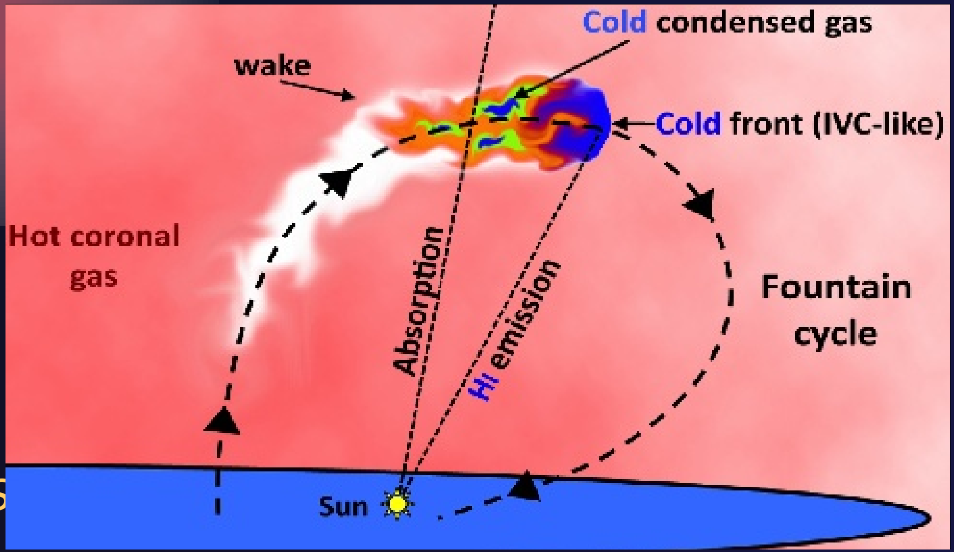
Cooling rate ~ 0.1 Mo/yr

Disc-corona interplay



Interface layer where disc and coronal materials mix

High metallicity *"cold"* gas (from the disc) mixes with low metallicity hot gas

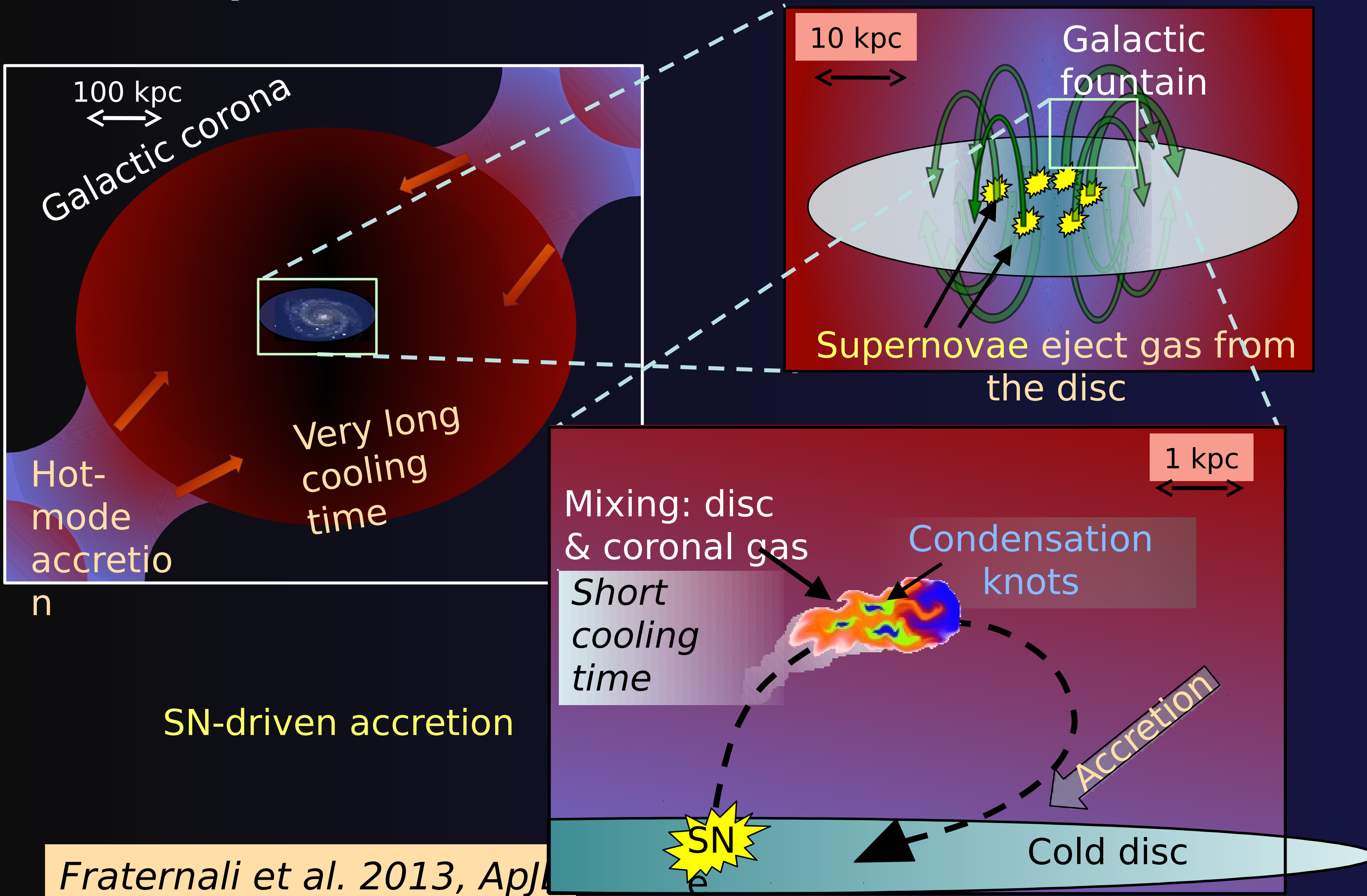


Fraternali & Binney 2008, MNRAS

Marinacci, et al. 2010, 2011, MNRAS

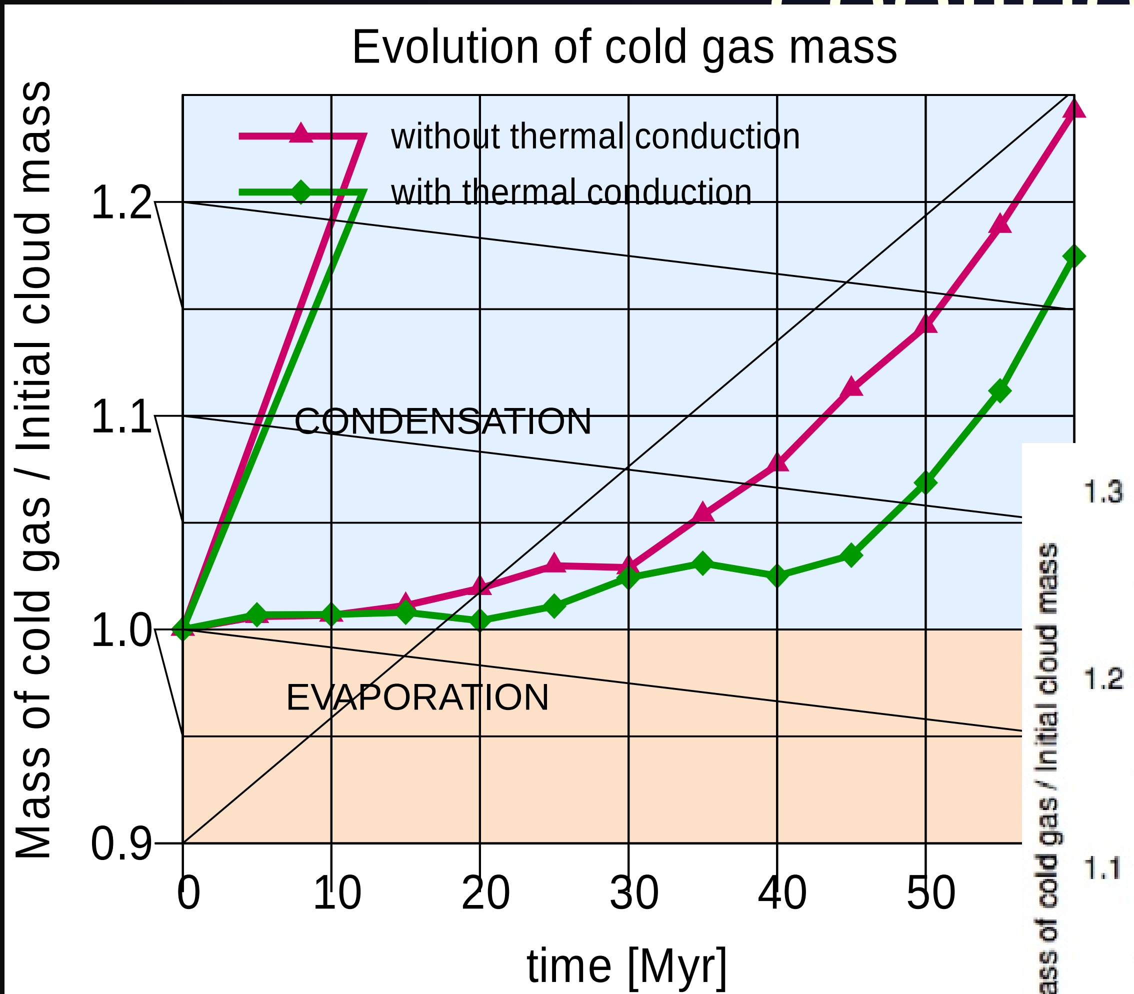
Marasco, Fraternali & Binney 2012, MNRAS

Supernova-driven accretion

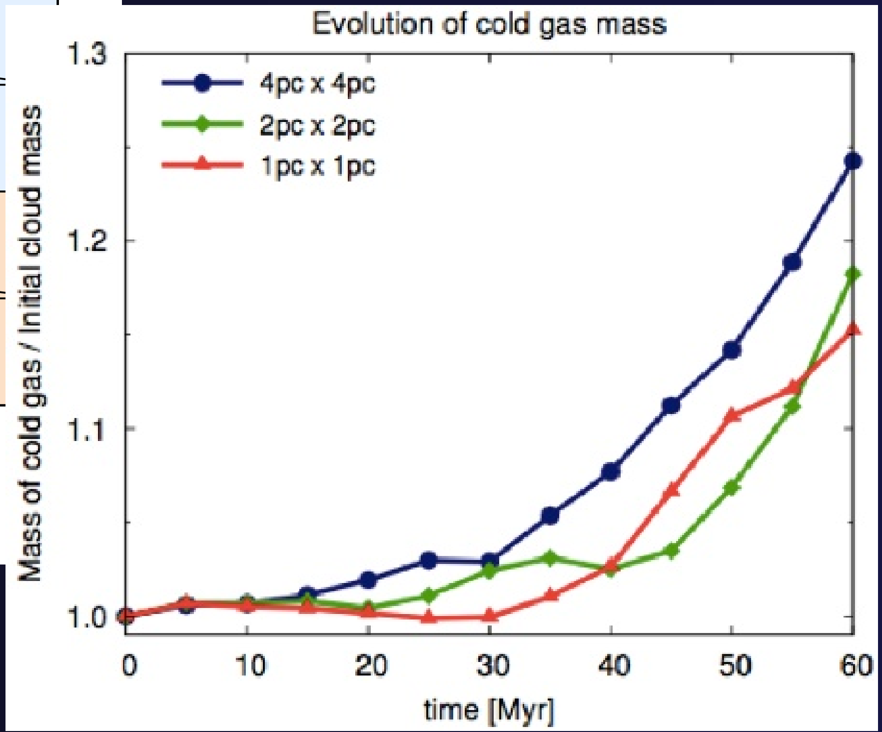


Fraternali et al. 2013, ApJL

Efficiency of fountain-driven cooling

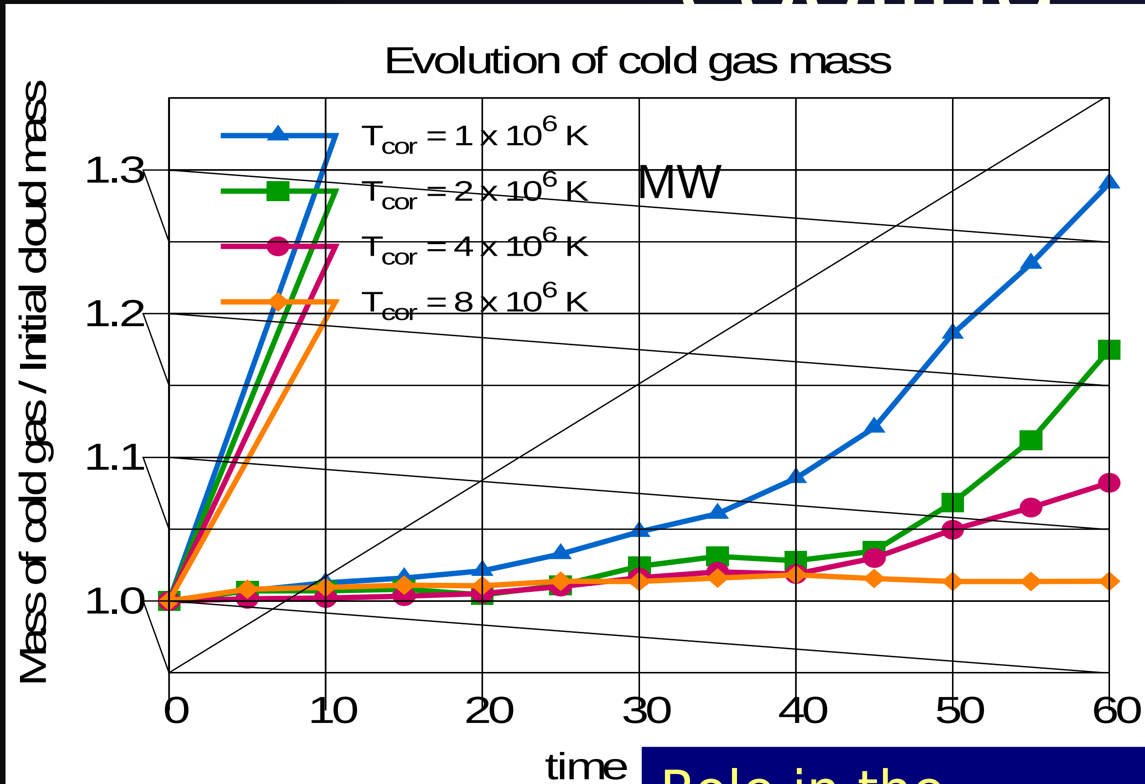


Convergence at ~ 2 parsec



Armillotta, Fraternali & Marinacci, in prep

Efficiency of fountain-driven cooling



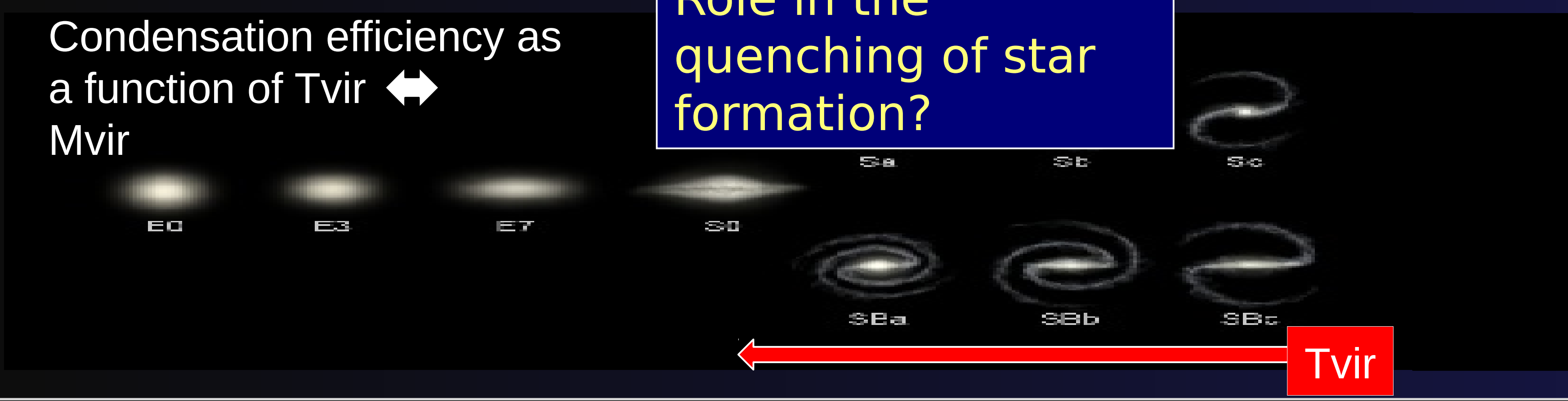
Condensation strongly depends on coronal temperature

At Tcor > 4 x 106 K clouds evaporate

Armillotta, Fraternali & Marinacci, in prep

Condensation efficiency as a function of Tvir ⟺ Mvir

Role in the quenching of star formation?

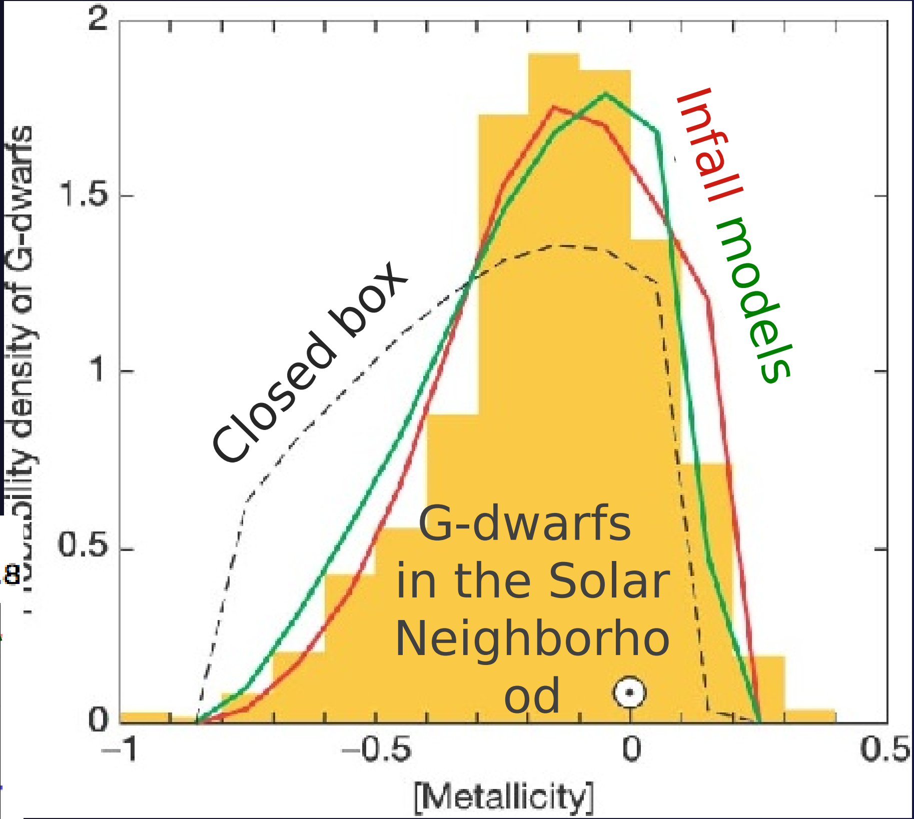


Milky Way evidence

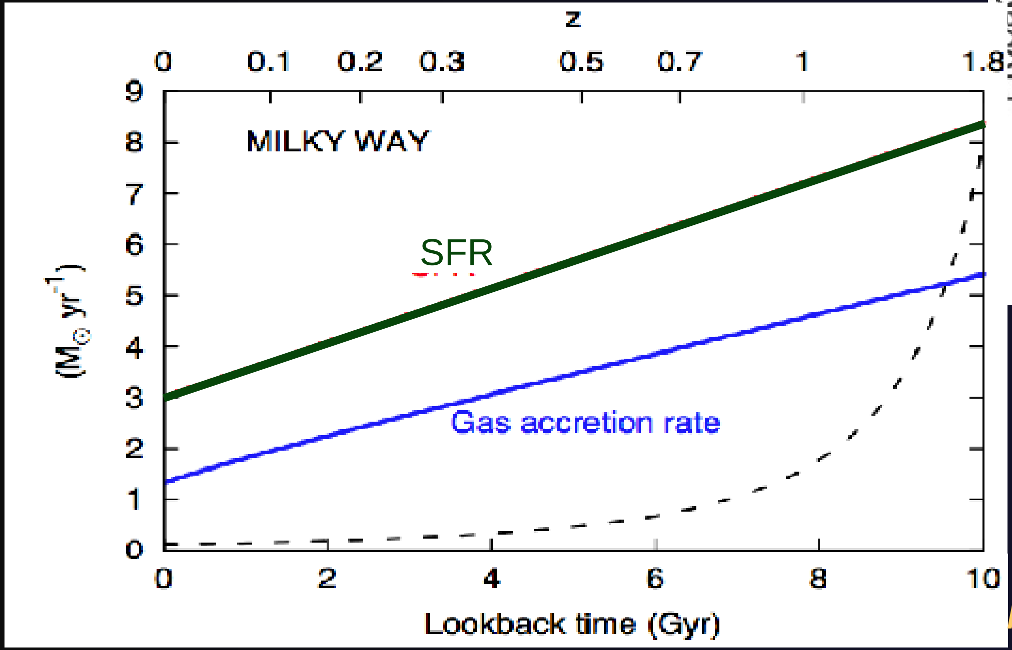
Chemical evolution models
G-dwarf problem
Larson 1972, Tynsley 80, Chiappini+ 97, 01; Schoenrich & Binney 09

Deuterium in local ISM appears to be re-supplied *Linsky et al. 2006*

Need for gas accretion at Z<~0.1



Dauphas et al. 2005, Nature

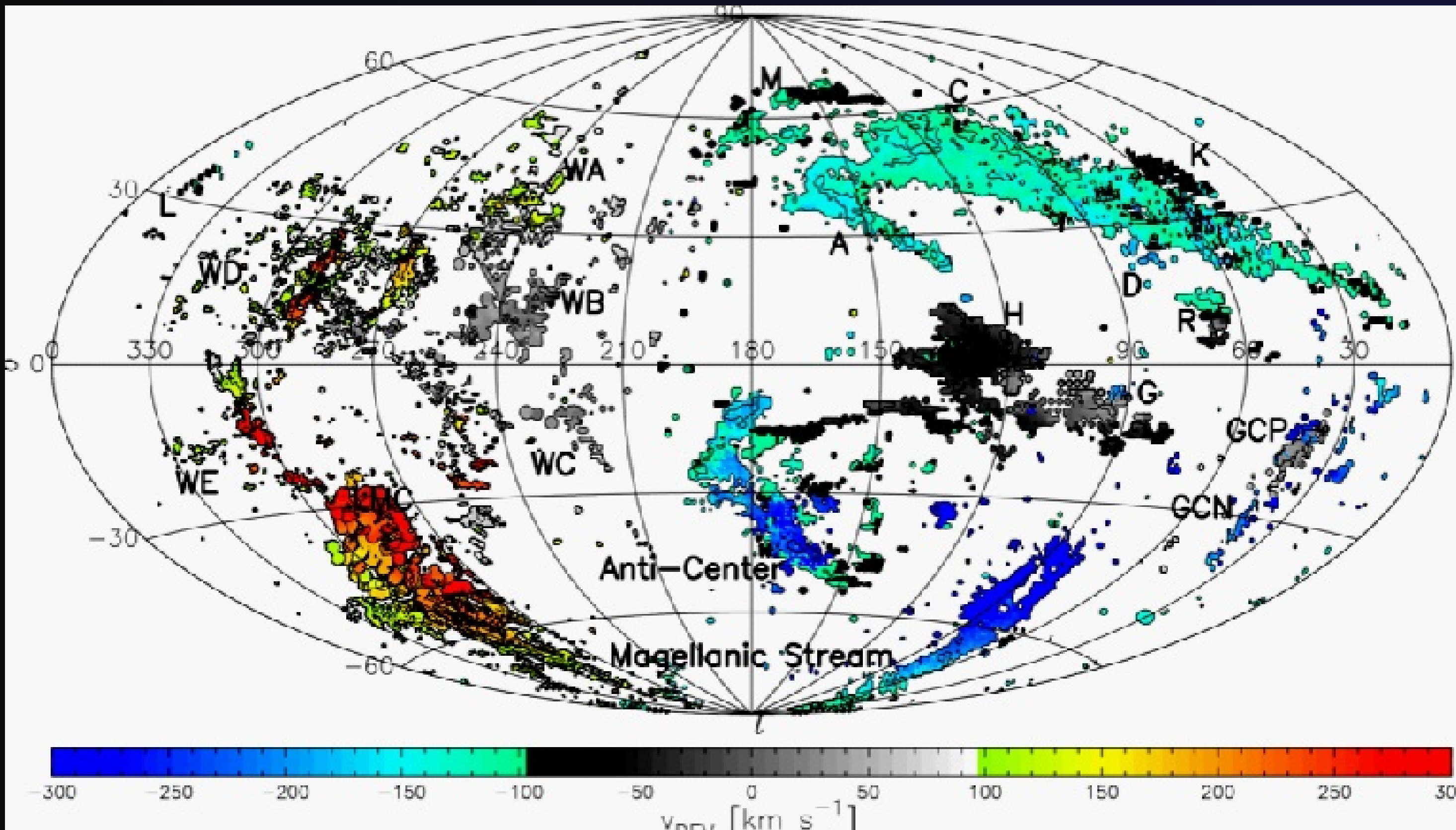


$$\mathrm{SFR} \propto \dot{M}_{\rm acc}$$

~ 1 M⊙/yr

Fraternali & Tomassetti 2012, MNRAS

HI High Velocity Clouds



Typical Distances: ~10 kpc

h~few-10 kpc

Z~0.1-0.4 Z⊙

M<107 M⊙

Wakker et al. 2007, 2008; Tripp et al. 2003

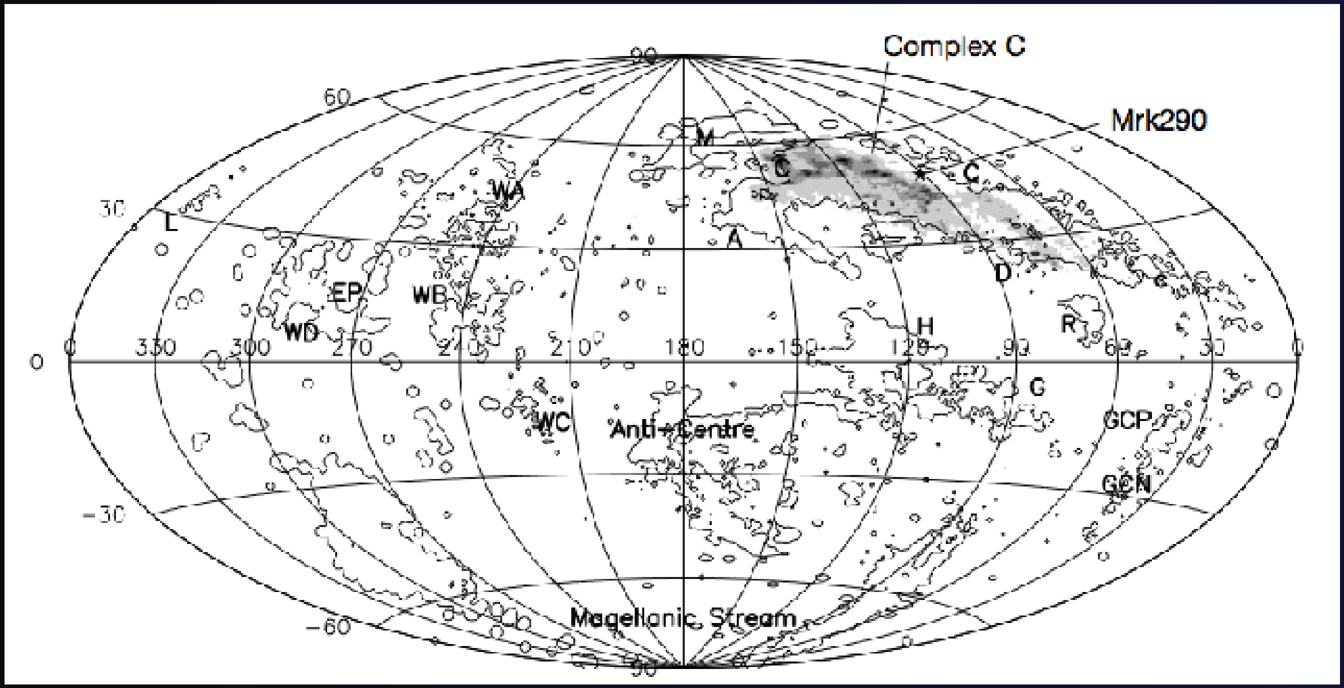
Accretion from High Velocity Clouds

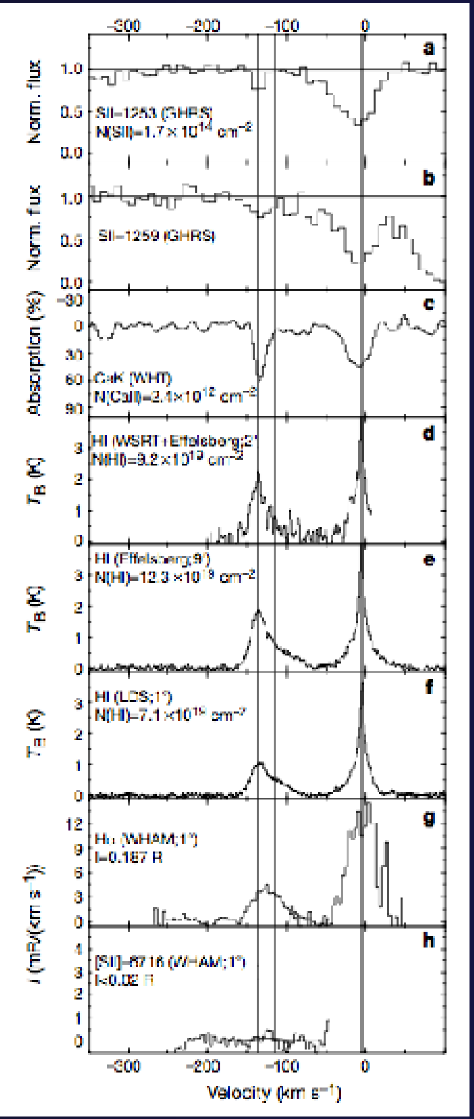
~ 0.08 M⊙/yr   Includes He and factor 2 of ionised gas!

HI HVCs cannot feed SF

Putman, Peek, Joung 2012, ARA&A

Origin of HVCs





Oort 70 leftover of galaxy formation
Bregman 80 Galactic fountain
+ satellites (*Olano 2001*), thermal instabilities (*Kaufmann+06*), no thermal instabilities (*Binney+09*), filaments (*Fernandez+12*)

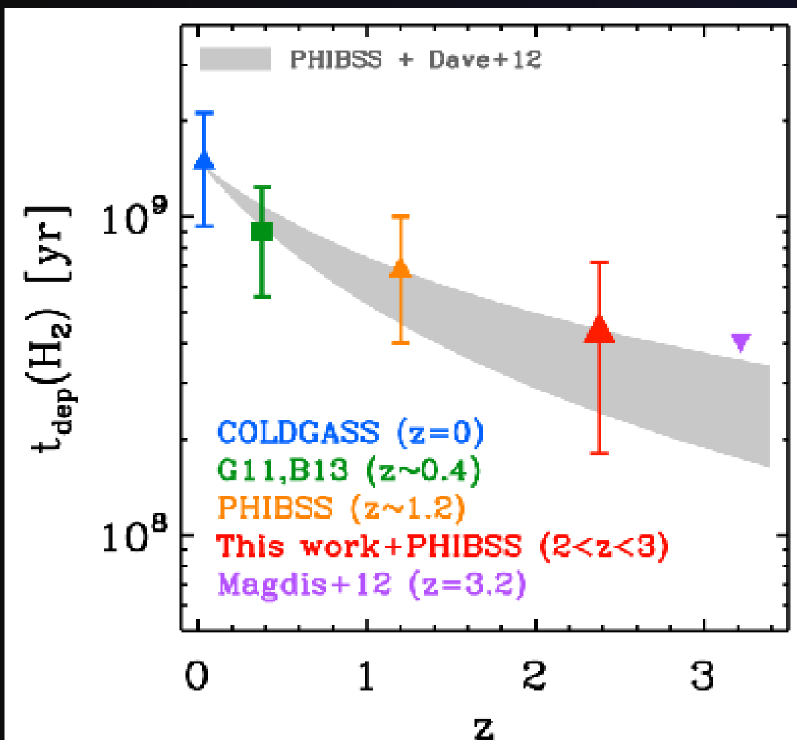
Wakker+ 1999, Nature Z~0.1 Solar -> Accretion!
Gibson+01 Z~0.3 Accretion?
Collins+07 overabundance α elements (SN II?)

Cosmology evidence

Gas depletion time ~ 1 Gyr

Assembly of stellar mass in the Universe

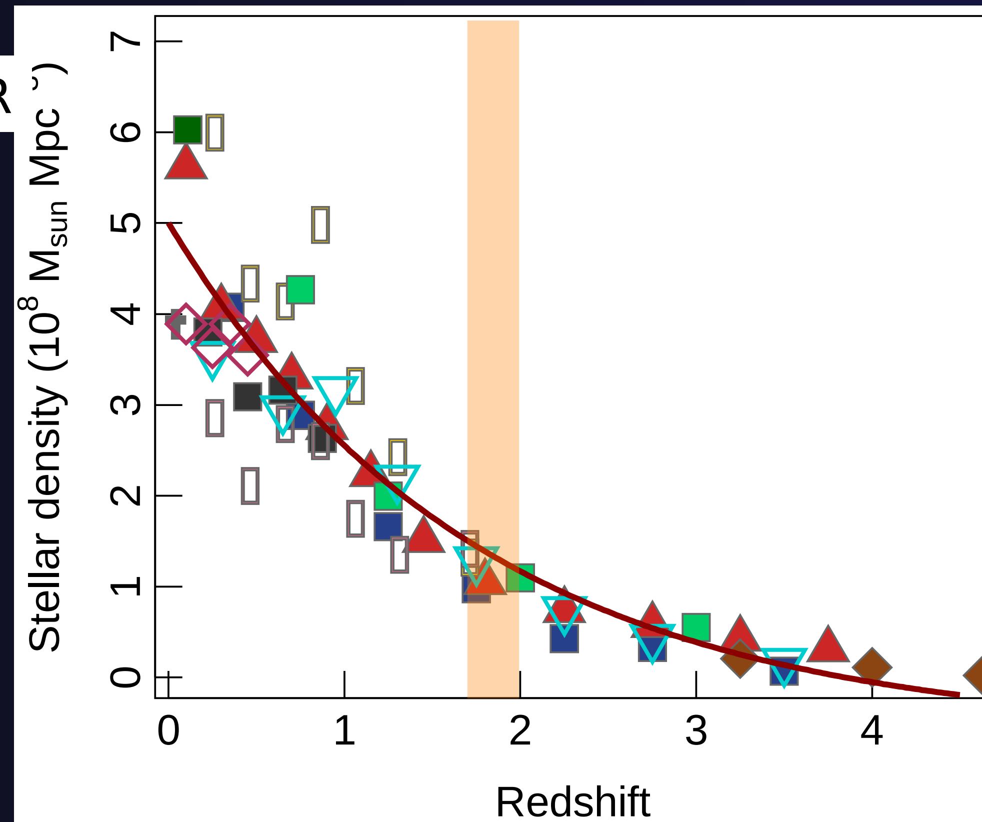
Gas depletion ti tdepl = Mgas / SFR



Saintonge+ 15

Kennicutt+83, Genzel+ 10,

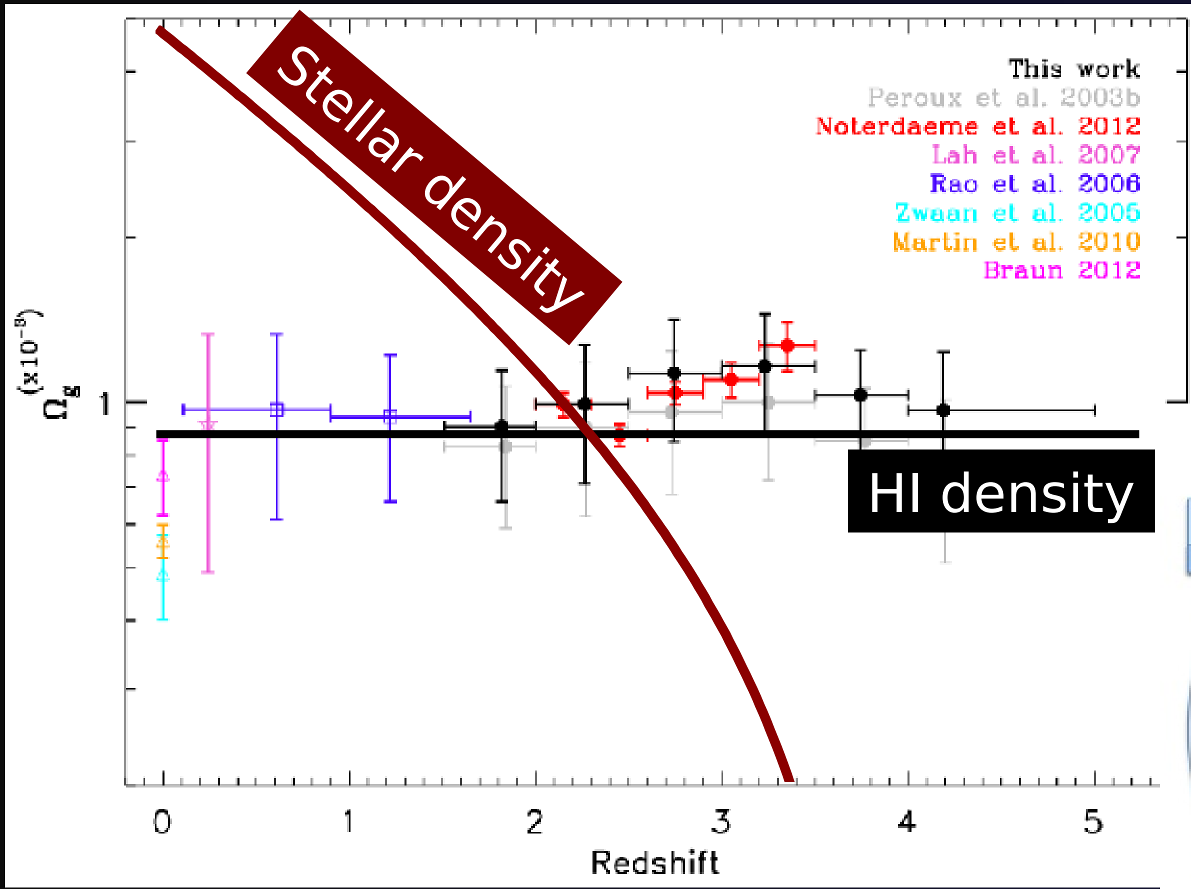
Bigiel+11, Genzel+15



Compilation from *Madau & Dickinson 2014*

Cosmology evidence

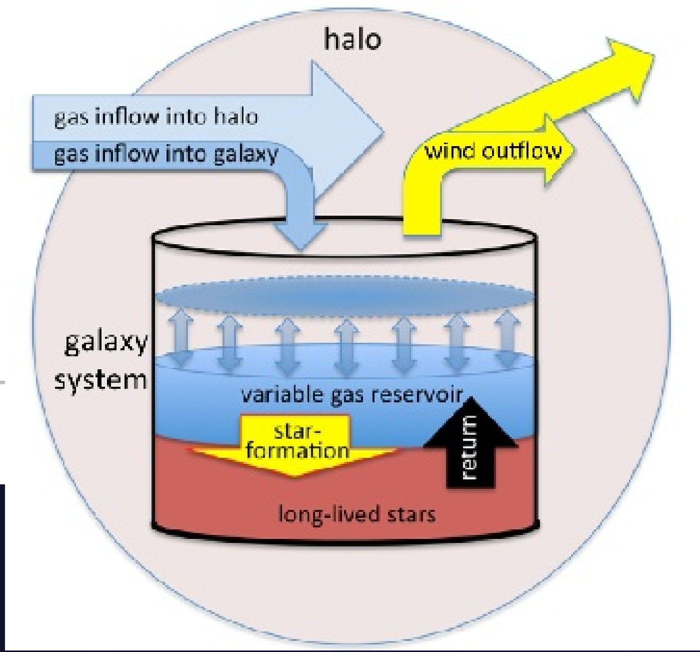
Constant HI in galaxies



Zafar+ 13

Accretion needed to keep forming stars at level of ~ SFR

Bathtub model

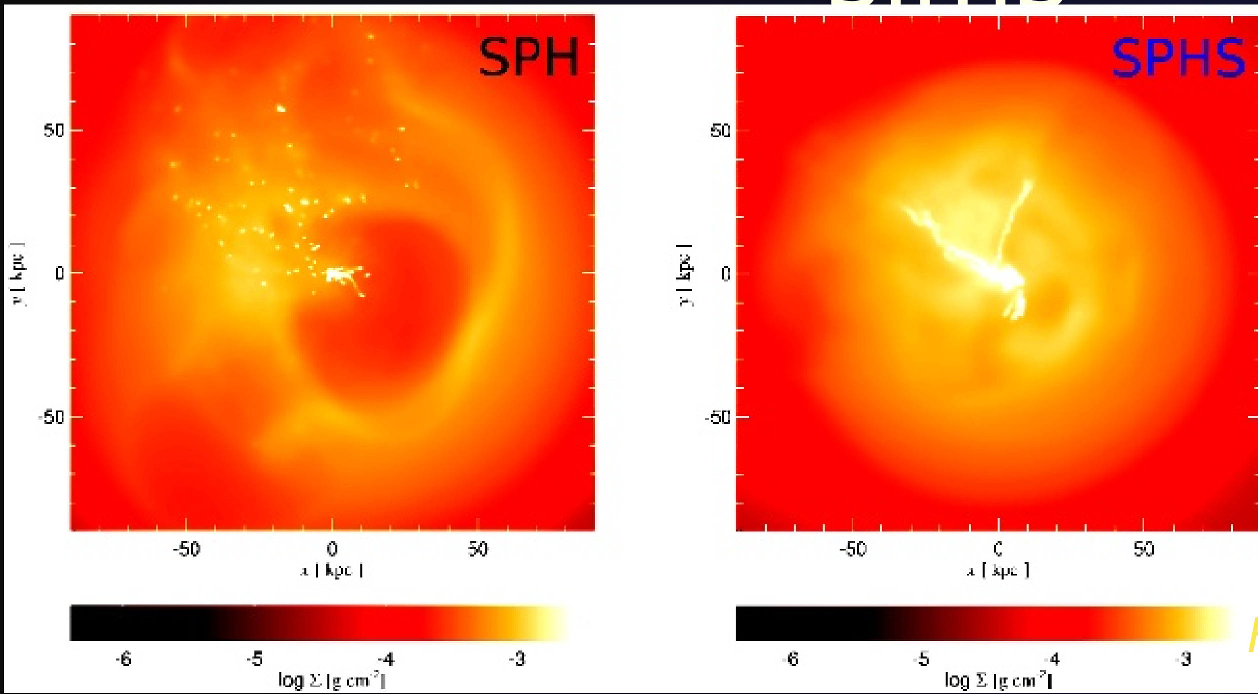


$$\mathrm{SFR} \sim \underline{\dot{M}_{\mathrm{acc}}} - \underline{\dot{M}_{\mathrm{outflow}}} + \underline{\mathcal{R}\mathrm{SFR}}$$

Bouché+2010, Davé+ 2012, Lilly+1

Supernova-driven accretion in other sims

SN-driven accretion in other sims



Modified SPH

No formation of clumps

"Cold gas condenses from the halo at the intersection of supernovae-driven bubbles. This positive feedback feeds cold gas to the galactic disc directly, fueling SF."

Hobbs et al. 2013, MNRAS

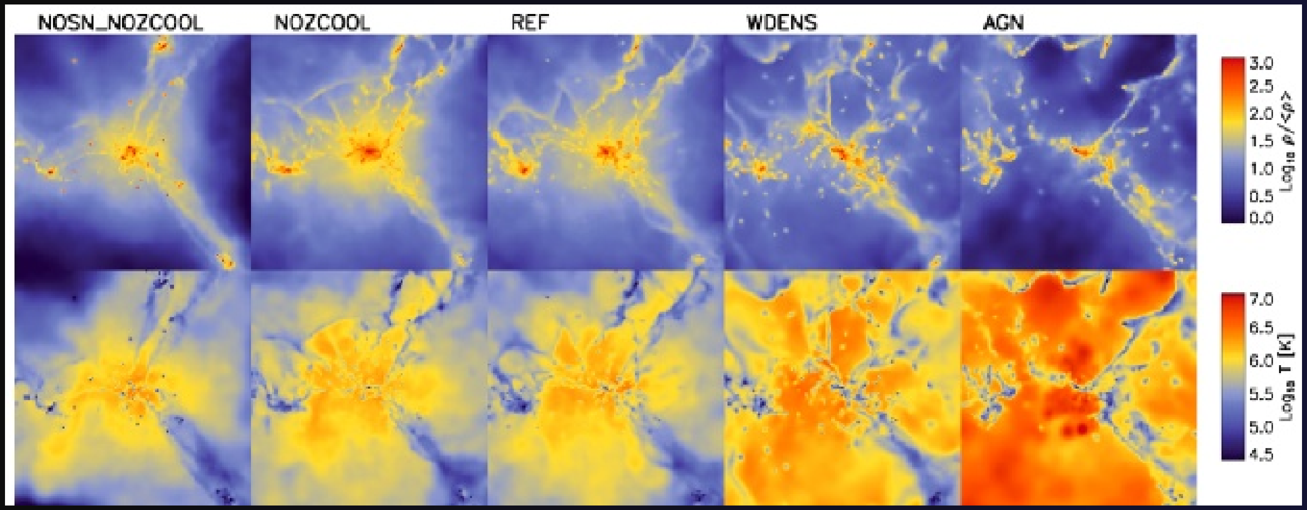
MaGICC - Gasoline

Halos enriched by galactic fountain

Gas in the fountain cycle comes back to the disk more metal poor!

Brook+12, Brook+13

Positive feedback is there

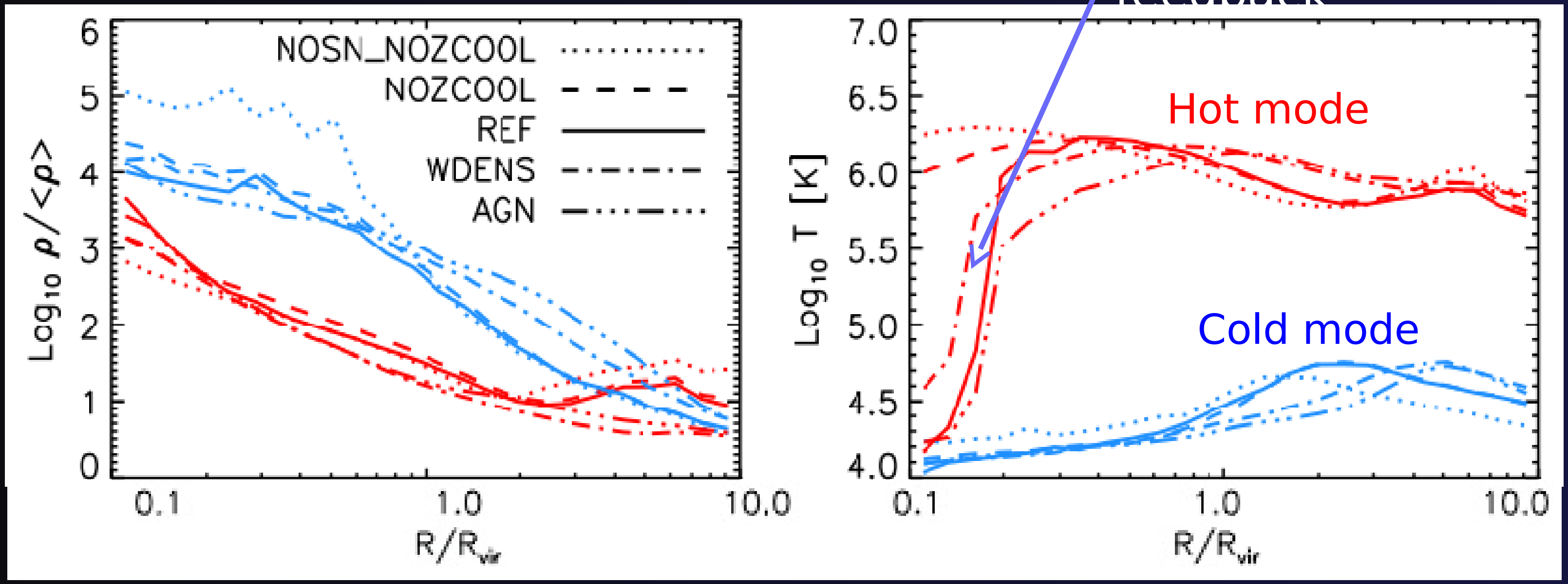


z=2

Cooling induced close to galaxies by metals ejected by feedback

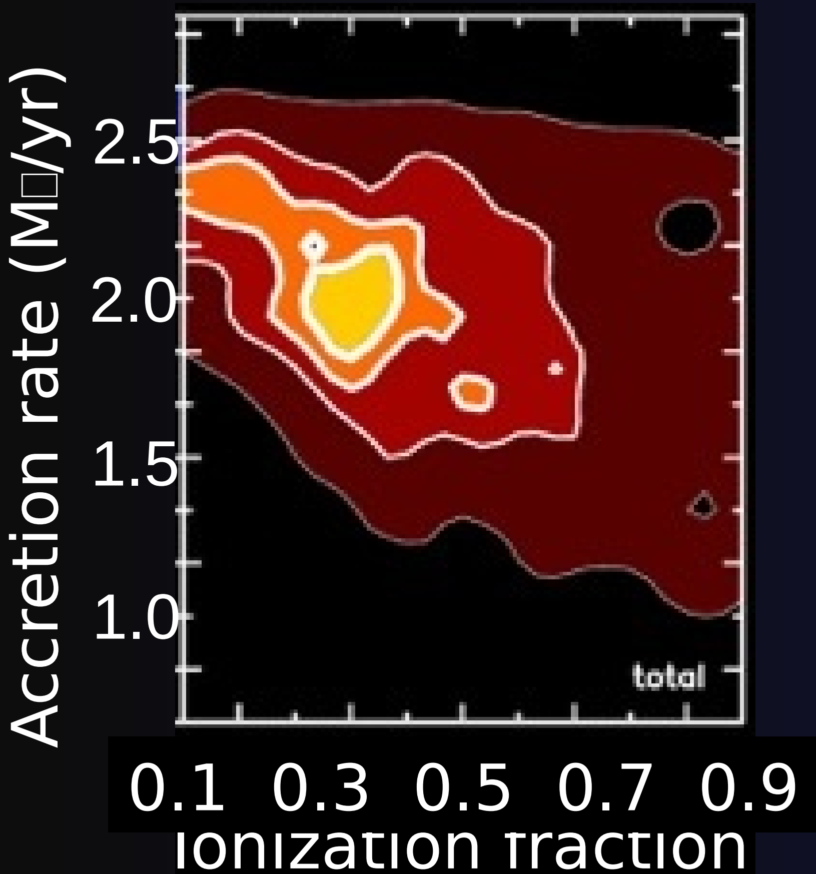
OWLS

GADGET-3



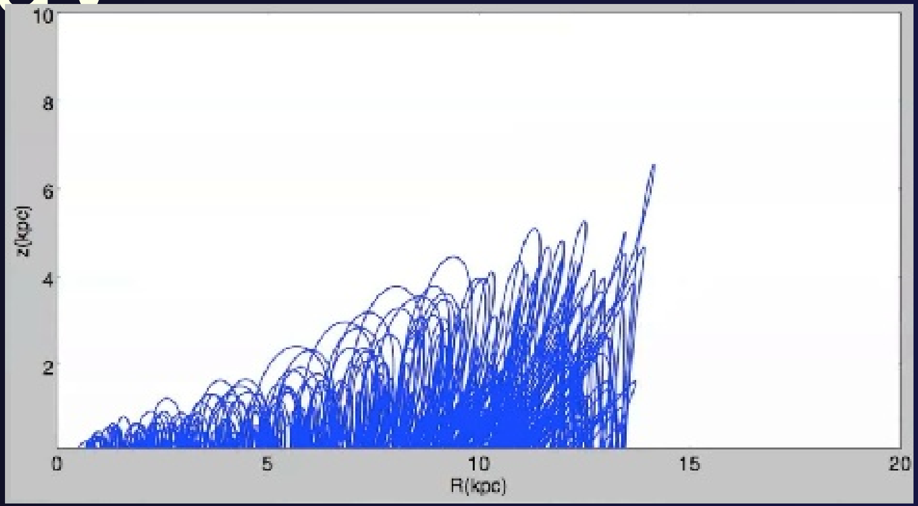
van de Voort & Schaye 2012

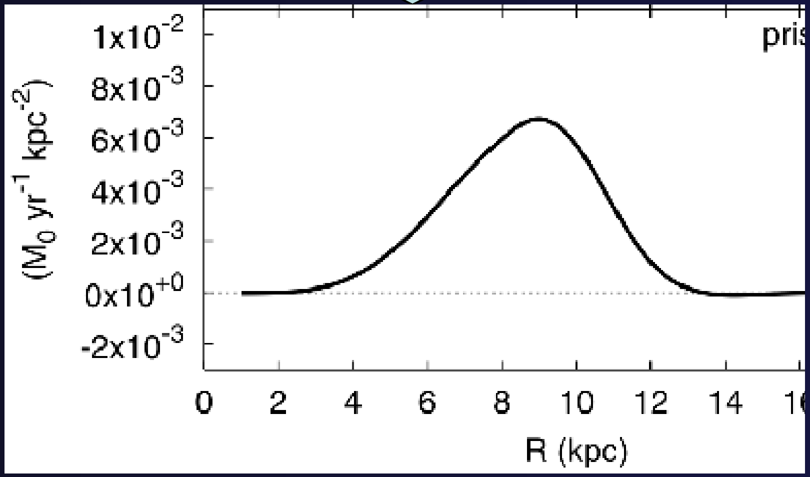
Extraplanar HI in the Milky Way



Best-fit Accretion Rate ~ 2 M□yr-1

Compare to SFR ~ 1-3 M□yr-1

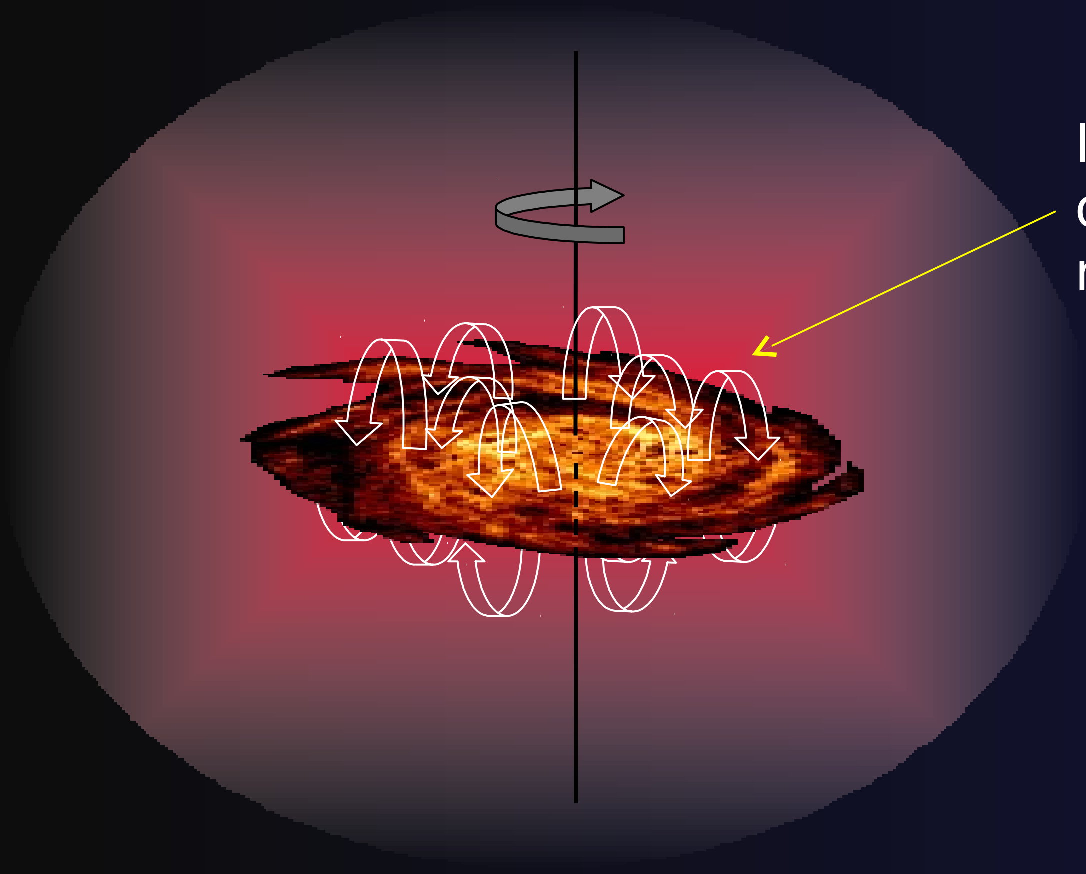




Marasco, Fraternali & Binney 2012, MNRAS

Accretion in the outer disc

Disc-corona interplay



Interface layer where disc and coronal material mix

Cooling time of the corona (typically very long) decreases dramatically because it is mixed with:

1. *cold* gas
2. High Z gas

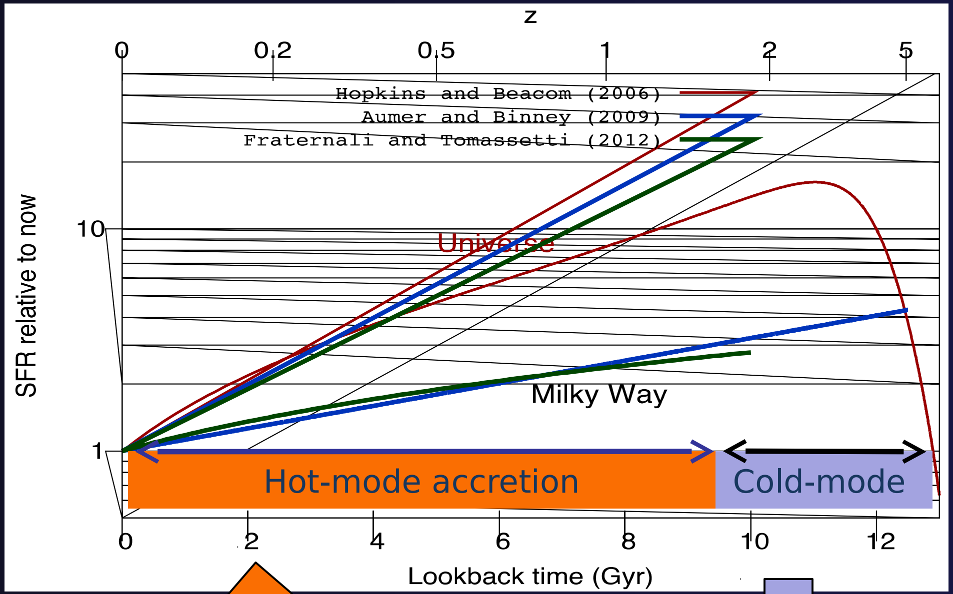
Fraternali & Binney 2008, MNRAS

Marinacci, et al. 2010, 2011, MNRAS

Marasco, Fraternali & Binney 2012, MNRAS

Implications for galaxy evolution

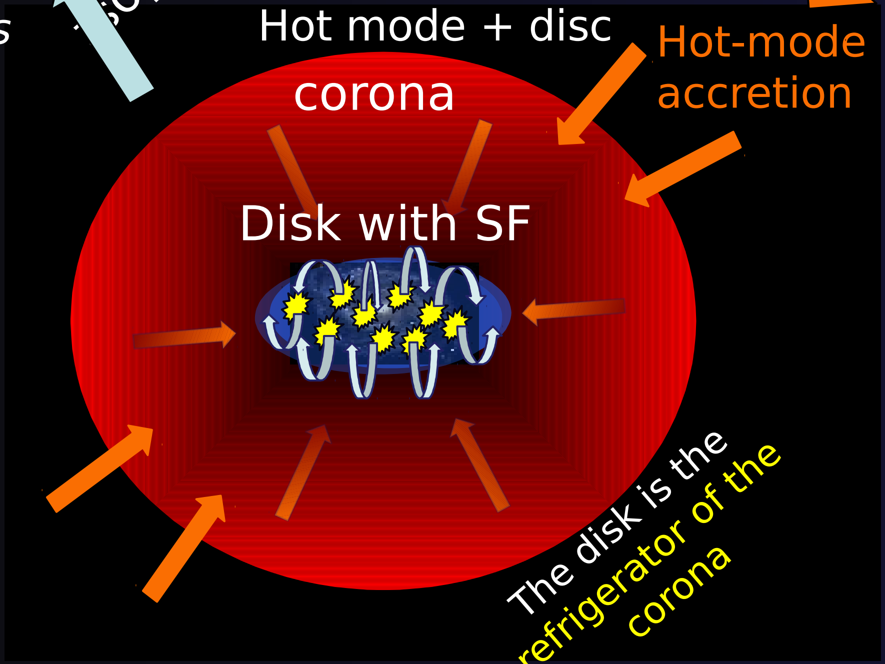
Evolution of discs



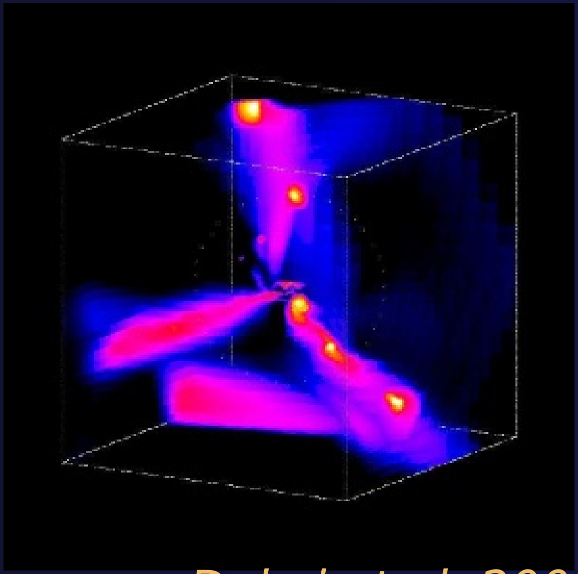
Red and dead

And the corona does not cool further

If gaseous disc is lost

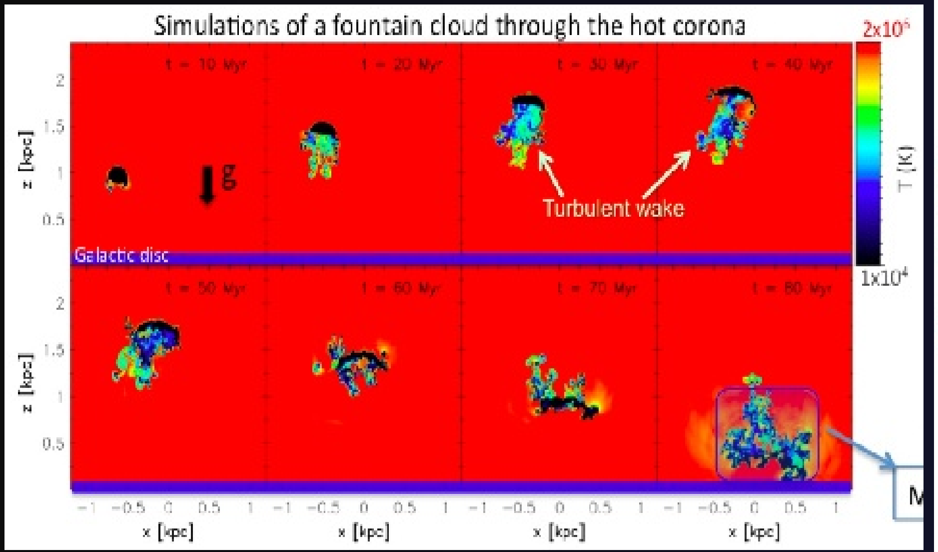


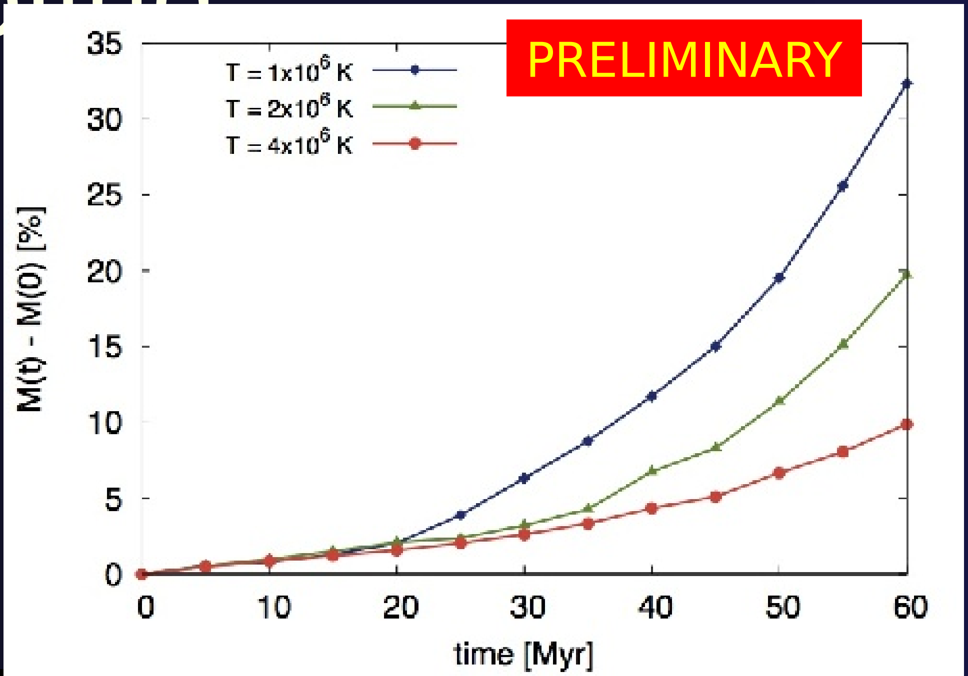
Cold mode



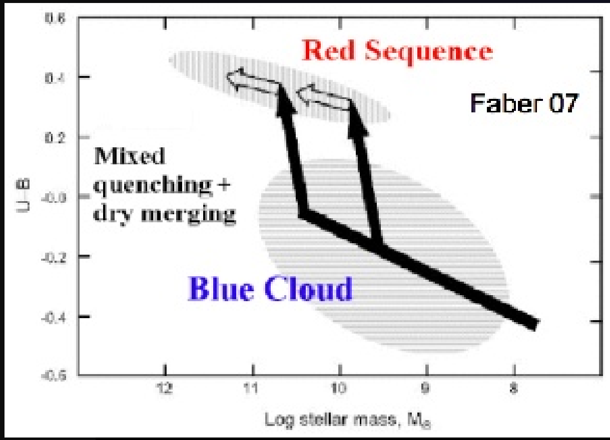
Dekel et al. 2009

Efficiency of SN-driven cooling



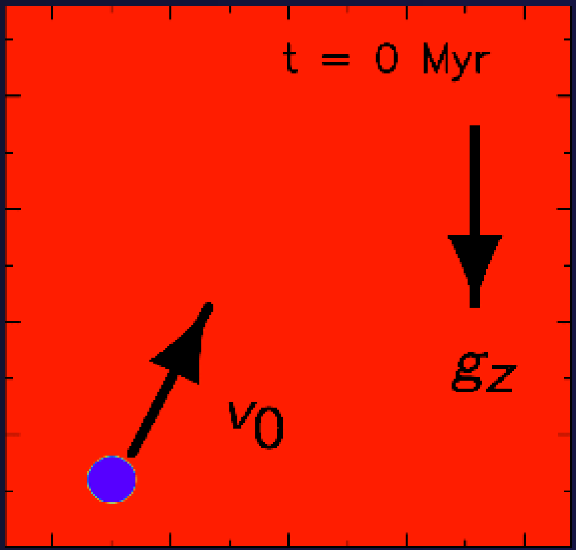


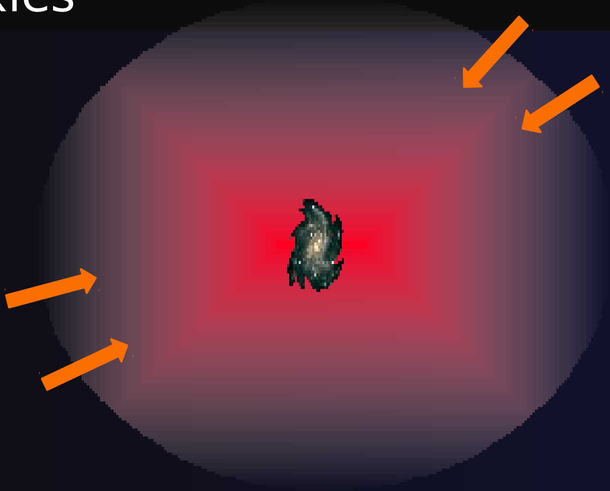
Armillotta+, in prep

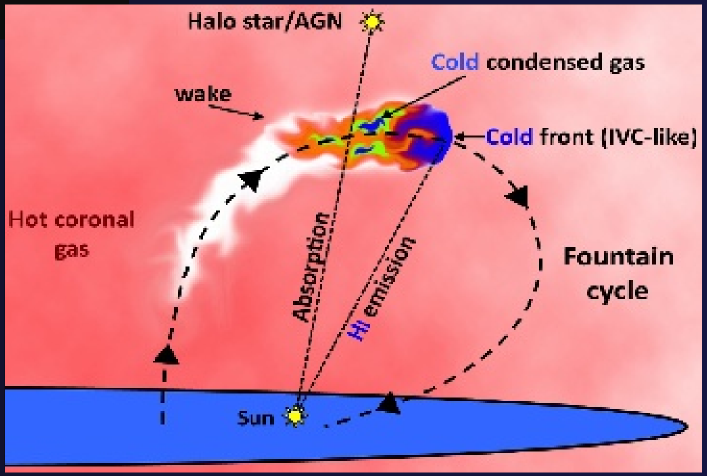


Conclusions

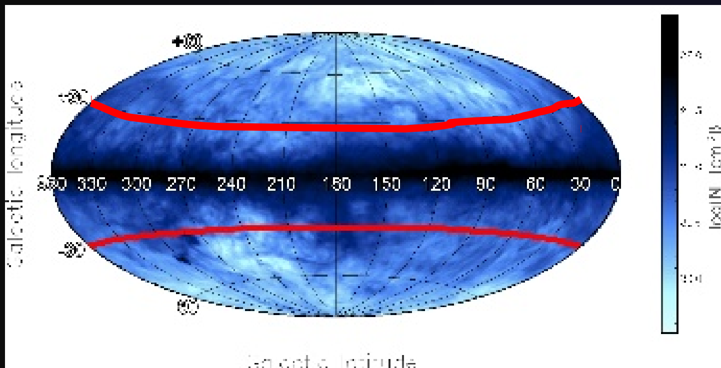
- Supernova feedback cools the corona in star-forming galaxies like the MW
- Very good fits:
  - HI in the MW and external galaxies,
  - ionized absorbers in the MW
  - This can be the way hot-mode accretion feeds star formation in disc galaxies



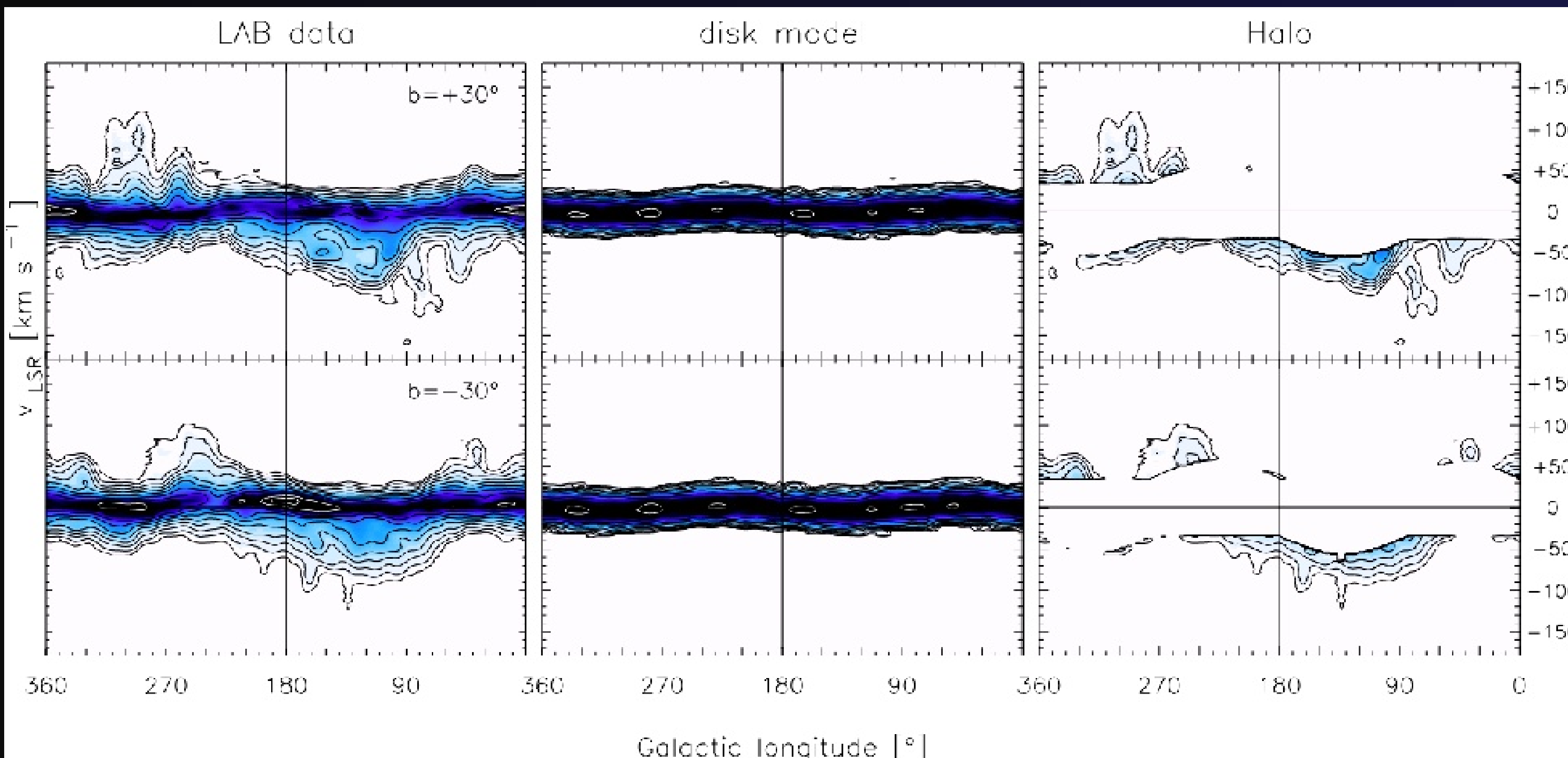




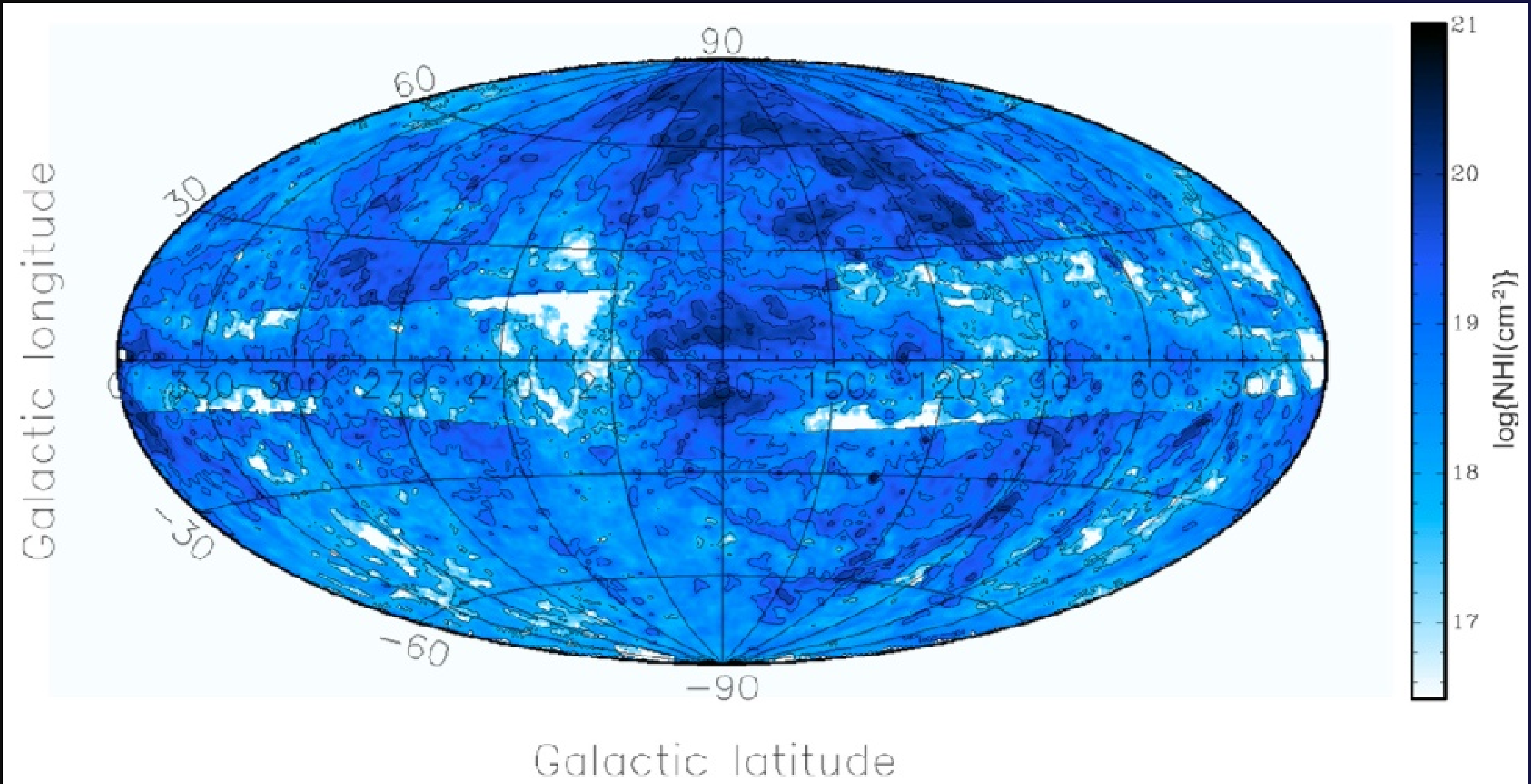
1. Extraplanar HI in the Milky Way



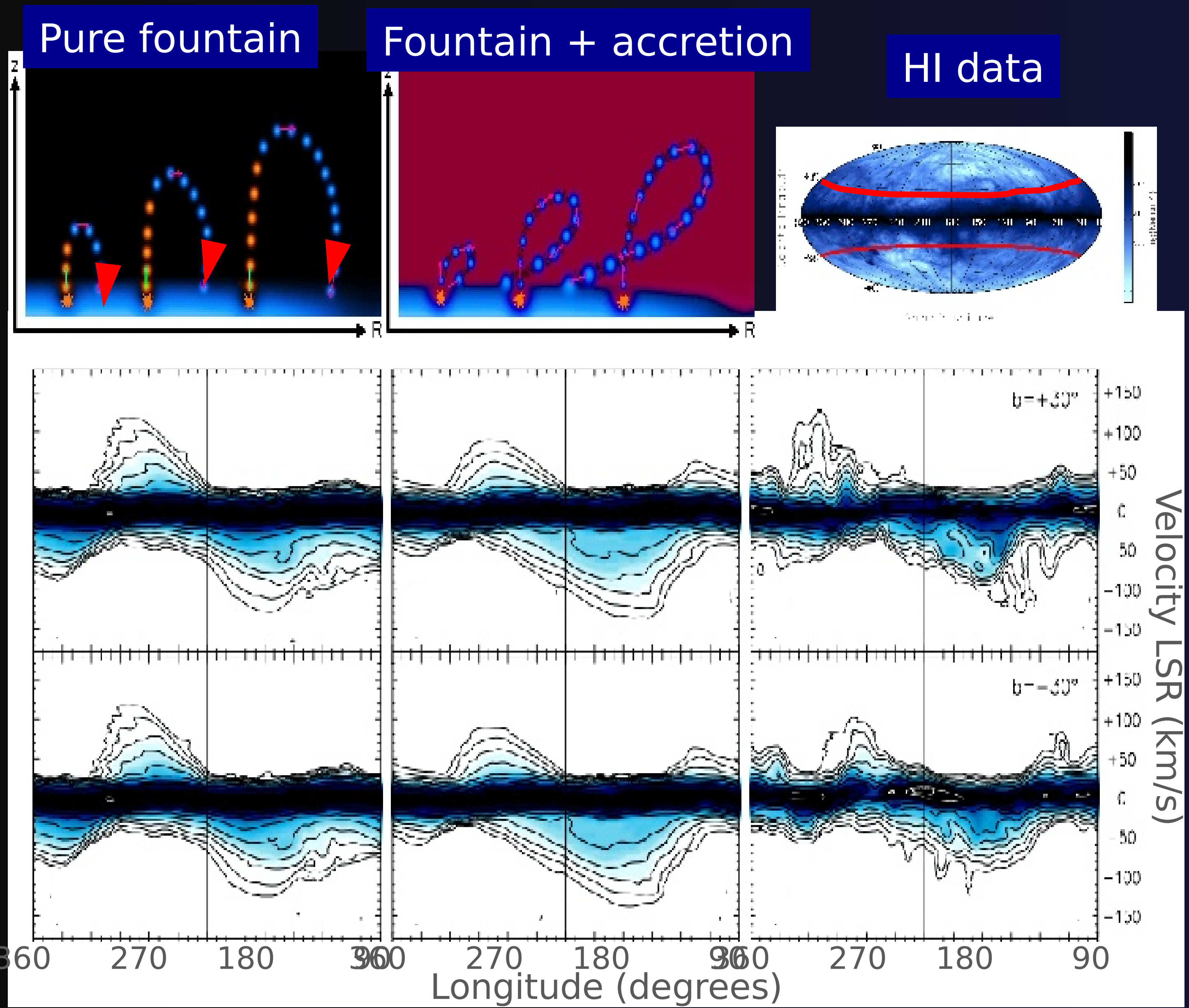
HI disk and halo in the Milky Way

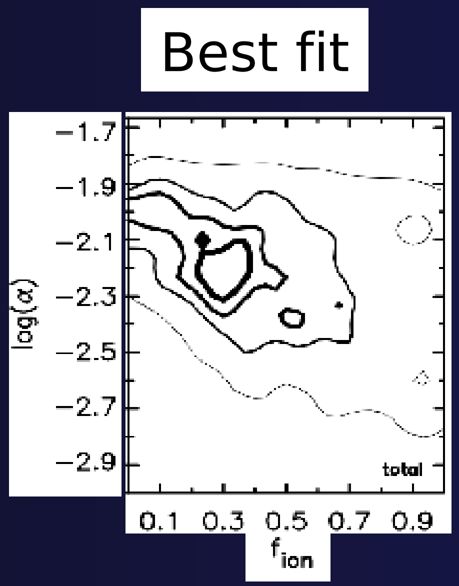


HI halo – all-sky



Marasco & Fraternali 2011, A&A





vk= 75 km/s
fion = 0.3

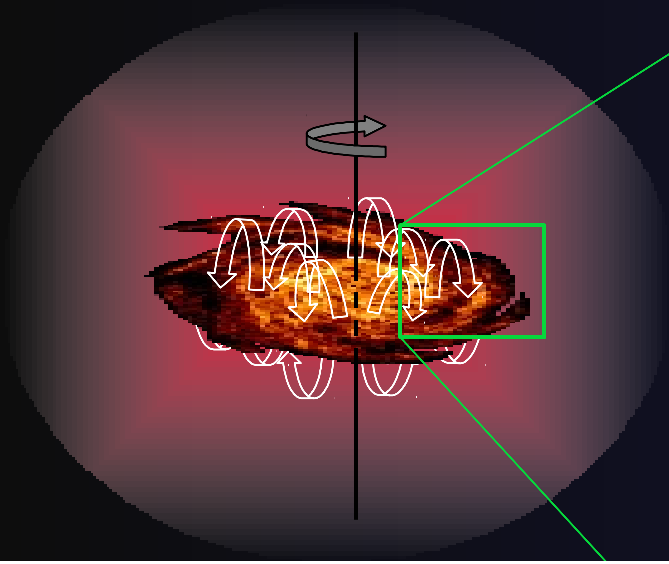
$\dot{M}_{cor} \sim 2\ M_\odot$/yr

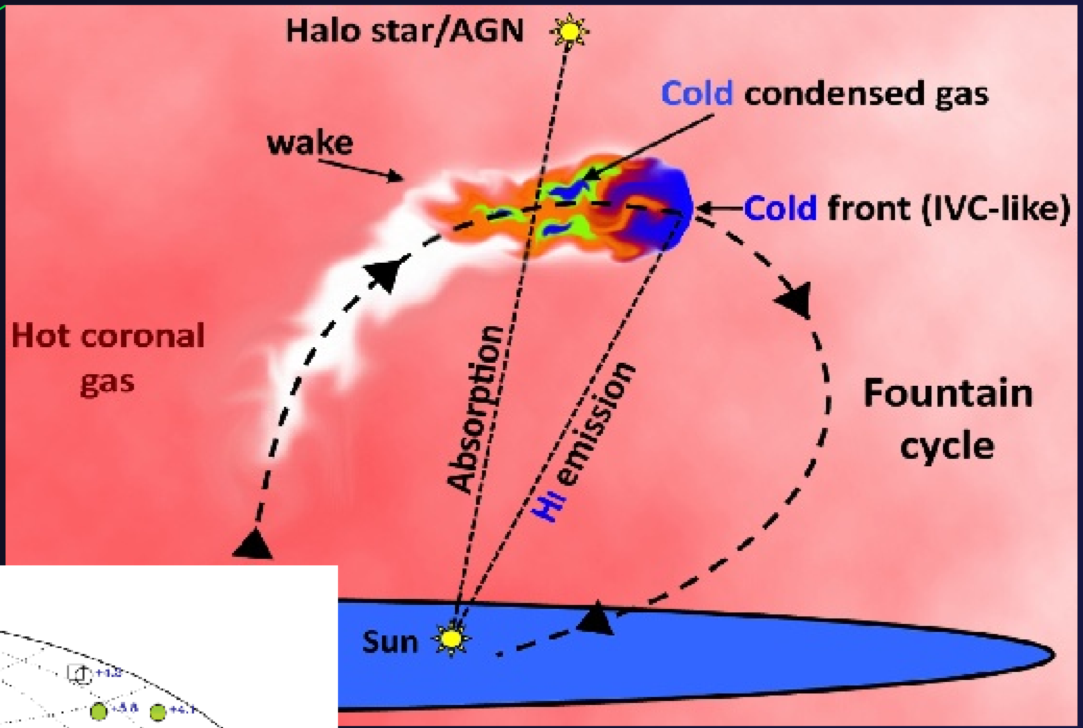
Marasco, Fraternali & Binney 2012

Halo gas:
~80% from fountain
~20% from corona

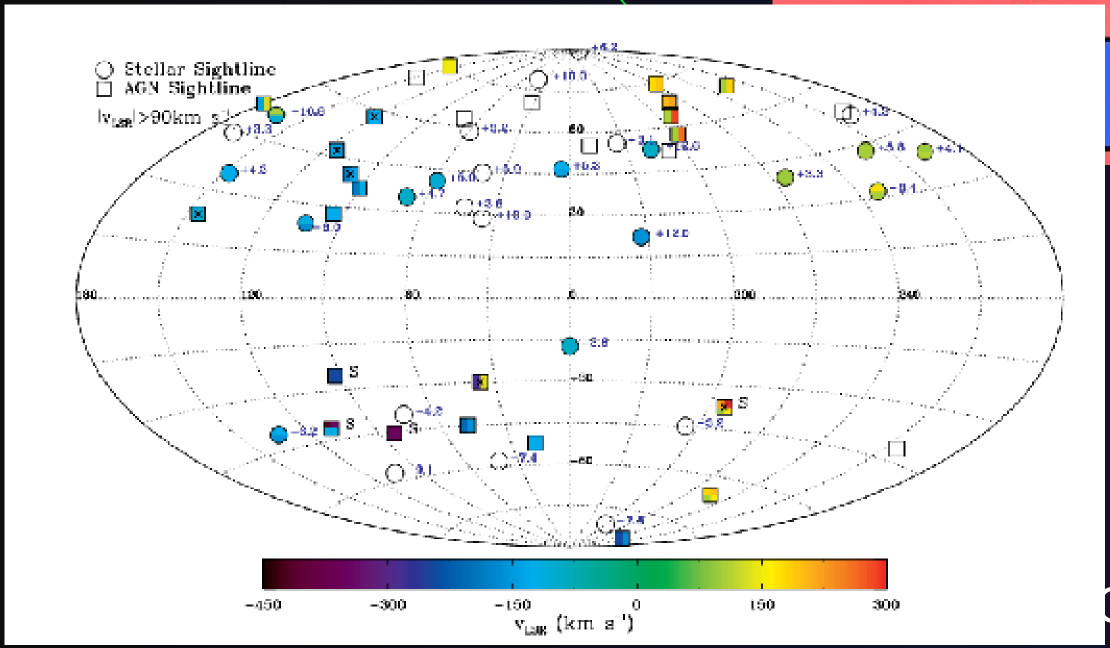
2. Absorption feautures

Cooling in the wake





Fraternali et al. 2013, ApJL



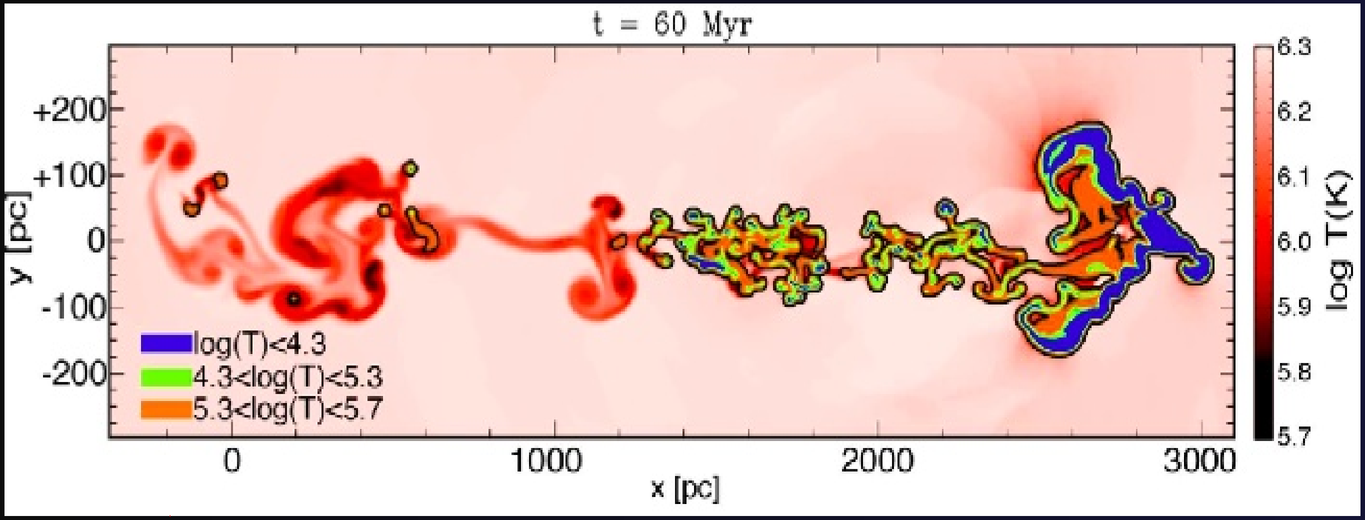
Shull+ 2009, ApJ

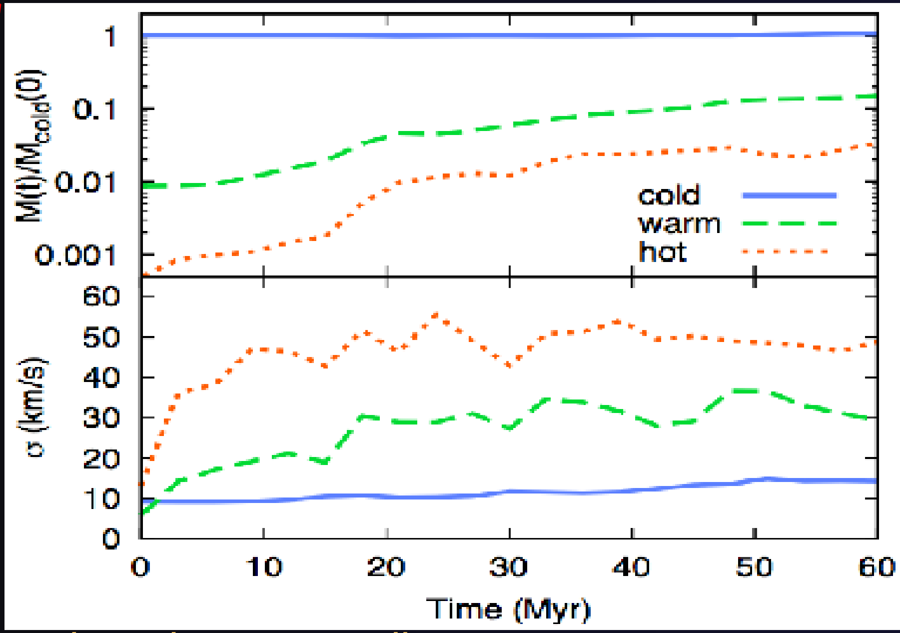
Lehner & Howk 2011, Science

Lehner et al. 2012, MNRAS

C II, Si II, Si III, …4.3<logT<5.3 K

Evolution of the wake



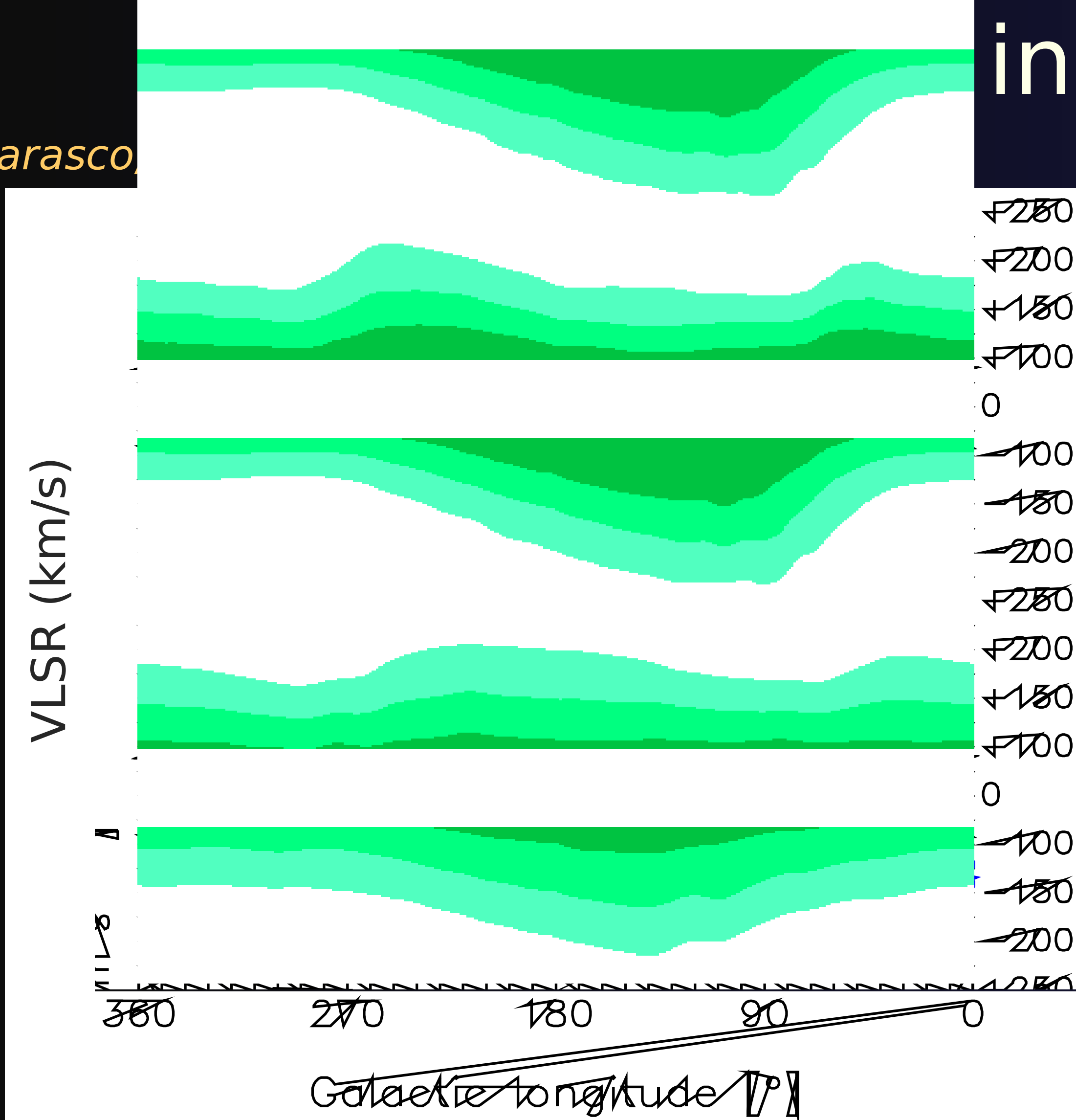


DYNAMICAL MODEL
for the IONISED GAS
(no free parameters)

Marasco, Marinacci & Fraternali 2013, MNRAS

in the MW

larasco,



Data from Lehner et al. 2012, MNRAS

This model reproduces:

- Positions & velocities of 95% absorbers
- Average column density
- Number of absorbers along the l.o.s.
- High velocity dispersions of absorbers

'Warm' accretion: ~1 $M_\odot$/yr